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STUDY OF SPACE ENVIRONMENT FABRICATION AND REPAIR TECHNIQUES

FINAL REPORT

DECEMBER 1966

AEROSPACE GROUP

HUGHES

HUGHES AIRCRAFT COMPANY
CULVER CITY, CALIFORNIA

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by

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ABSTRACT

The Materials Technology Department of the Hughes Aircraft Company has performed a research and development program for the past eighteen months under Contract No. NAS 9-4548 with the Manned Spacecraft Center, Houston, Texas. The objective of this program was to study a broad spectrum of joining techniques which might be suitable for fabrication and repair of structures in an extraterrestrial environment, select the two most promising methods and perform a feasibility demonstration test.

The following joining methods were studied:

1. Electron beam welding
2. Resistance welding/brazing/soldering
3. Thermochemical brazing
4. Tungsten arc welding
5. Adhesive bonding
6. Explosive welding
7. Diffusion bonding and pressure welding
8. Gas welding
9. Focused sunlight joining
10. Laser welding

Upon recommendation by NASA-MSC personnel, the following materials and gage thicknesses have been evaluated:

Material Combination	Gage Thickness, Inches
2014 Aluminum to self	0.013, 0.020, 0.032
AZ31B Magnesium to self	0.060, 0.070, 0.080
6Al-4V-Titanium to self	0.032, 0.063, 0.090
Inconel 718 to self	0.040, 0.070, 0.125
6Al-4V-Titanium to Inconel 718	Gages noted above

Electron beam welding and resistance welding/brazing/soldering were the two methods selected for feasibility demonstration and test. While both are feasible, neither of them is universally applicable, per se, to all fabrication and repair requirements.

Tests have shown that electron beam welding will be an excellent method of joining items 3 and 4 in preceding table, a poor method of joining item 2, rather impractical for item 1 because of the tooling required to prevent buckling of the thin gages and a very poor method of joining item 5. Resistance soldering techniques appear feasible for all of the materials combinations. This is quite fortunate since the two methods tend to complement each other.

Sound, quantitative engineering data concerning the strength, hermeticity and reliability of joints in typical materials and gage thicknesses have been obtained. This information, will be of tremendous value to designers of space structures. In addition the effort has identified certain problems related to joint design, tolerances and metallurgical compatibility.

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ILLUSTRATIONS

INTRODUCTION

This report is submitted as a final technical summary of the work performed to determine the feasibility of developing joining systems for extra-terrestrial repair and fabrication of structures.

The work was performed by the Materials Technology Department of the Hughes Aircraft Company, Culver City, California for the Manned Spacecraft Center of the National Aeronautics and Space Administration under Contract No. NAS 9-4548.

This report is organized in four major sections covering the work performed in (1) the selection of the two most feasible joining methods, (2) demonstration of their feasibility by mechanical testing, (3) determination of hermeticity of joints produced by the two processes and (4) an annotated bibliography.

DEFINITION OF SYSTEM REQUIREMENTS

OPERATING CONDITIONS

Spacecraft Cabin and Lunar Environments

The atmosphere and temperature of the spacecraft cabin has been proposed as one similar to that experienced by man on earth. Thus the artificial cabin atmosphere would consist of 100 percent oxygen at 5 psia or 50 percent oxygen, 50 percent nitrogen at 10 psia. Temperature aboard the spacecraft should approximate 70°F. Consequently, it is anticipated joining problems would be encountered where the materials and combustion gases, employed in generation of heat would react with the cabin atmosphere. Another environmental factor relevant to development of successful joining techniques is the gravitational force within the spacecraft which can vary from nearly zero to one g. The critical disadvantage of a low gravitational force field concerns "levitation" effects on molten weld metal causing it to "ball-up" and literally float away during welding.

The environment postulated for the lunar surface is assumed to consist of an atmospheric pressure ranging from 10^{-6} to 10^{-9} Torr, or less, and temperatures from -250°F to +250°F. Temperature is anticipated to be a minor factor influencing the achievement of successful welding methods, but could have profound effects on joint reliability due to stresses induced by thermal cycling. However, a "hard" vacuum environment may result in problems of molten weld metal sublimation. Additionally, a low atmospheric pressure involves problems related to control of joining temperatures and waste heat dissipation. These joining problems may be minimized by steep thermal gradients, and small melting zones as may be achieved by electron beam welding. Resistance welding also provides an attractive feature of protecting the molten metal zone from vacuum during welding. Employing either welding method, the lunar vacuum provides volatilization of surface oxide films and elimination of re-contamination of cleaned surfaces.

Human Factors

In addition to basing the choice of a space joining method on metallurgical and environmental factors, pertinent human factors must be given consideration. Consequently, the candidate space fabrication techniques must be evaluated regarding their degree of practicality for operation in a space cabin or extraterrestrial environment. The following are salient features which influence the choice of potential joining techniques and the associated equipment:

1) Ease of utilization by astronaut (degree of complexity of the operation).
2) Mass and geometry of joining equipment.
3) Application to joining various structural geometries.
4) Reliability of weldments performed.
5) Maintenance and repairability of equipment.
6) Operator safety

The initial factor, ease of utilization, is of major significance since the astronaut may be limited in his degree of manual dexterity due to his cumbersome space suit and associated equipment. Additionally, it may be assumed the astronaut has developed only limited expertness and judgement in the operation of the joining equipment. Therefore the operation of the joining equipment should be aimed at a degree of simplification equivalent to "pushing a button".

Because of weight, storage and transference limitations of equipment deployed in space applications, the mass and geometry of joining equipment must be minimized. Fabrication of space vehicles may involve varying and complex geometries requiring joining equipment capable of following the various contours described by the space structure designs.

It is of a highly critical nature that the fabricated space vehicles be free of joining defects which would imperil their functioning. Hence a high degree of reliability must be incorporated into the joining process to prevent vehicle failure that would jeopardize the success of the space mission.

Low maintenance of the joining equipment is highly desirable since facilities for repair would not be available.

Of highest importance in the final analysis is the safety of the operator. Joining equipment must be chosen which will minimize danger to the operator, e.g. no usage of spontaneously combustible fuels for generation of heat energy, or liberation of gases that would "poison" the cabin atmosphere, minimization of shock and radiation hazards, etc.

MATERIALS AND GAGES

Materials for space environment fabrication have been chosen on the basis of their meeting three basic requirements. The first is their ability to be exposed to a space environment without incurring severe damage from corpuscular radiation, particle bombardment, and temperature ranging from approximately +250°F to -250°F. A second factor is their high strength-to-weight ratio and low bulk density. A final factor concerns their ability to be joined in space cabin and lunar surface environments. Based on these criteria, 2014 aluminum, 6Al-4V titanium, Inconel 718, and AZ31 magnesium were chosen for investigation in this program. These materials and the range of gages to be joined are presented in Table 1.

MATERIAL COMBINATIONS	GAGE, inches
2014-T6 Al-2014-T6 Al	0.012 to 0.032
6Al-4V Ti-6Al-4V Ti	0.030 to 0.090
Inconel 718 - Inconel 718	0.040 to 0.125
6Al-4V Ti-Inconel 718	0.030 to 0.090
AZ31 Mg-AZ31 Mg	0.060 to 0.080

Table 1

JOINING SYSTEM ANALYSIS

ELECTRON BEAM WELDING

This process has probably the highest potential for use in an extra-terrestrial environment of all the joining methods evaluated in this study. The technology is fairly well understood, the process can be readily automated to simplify operator control, it is applicable to a broad range of materials including all of those involved in this study and because of the steep thermal gradients resulting from the high energy densities used, it is probably the most efficient process possible from the standpoint of energy utilization. The chief drawback is the bulk and mass of the power handling equipment required but this problem is under scrutiny by other contractors and should be resolvable.

Some of our early studies showed energy utilization efficiencies to be as high as 90 percent. This factor varies as a function of the thermal diffusivity of the material, in all probability. It also appears to vary in proportion with the specific energy input, that is, high specific energy input welding is more efficient than lower energy welding. Work is still being performed to verify these hypotheses. Some additional work is also being performed to evaluate the relationship between accelerating voltage and the depth of penetration of fusion in various metals. This subject is particularly confusing because of the complex interrelationships of power, speed of welding and focus. Extensive effort has been directed toward this problem in an attempt to resolve these relationships so that a clear definition of the lowest possible voltage, power and focus current necessary to make satisfactory welds in the requisite metals and gages can be determined. The net effect of this effort is to minimize the mass of the system from the standpoint of insulation, transformer size, weight, etc.

Tests have been performed to determine the factors of gun geometry that significantly control the power output of the electron gun. This study was done to obtain a means of controlling the gun to produce both constant power and constant specific energy.

Other tests have been directed toward the determination of the relationship of focus coil current and accelerating voltage. Preliminary work showed this to be an essentially linear relationship.

It is believed that the potential universal applicability of electron beam welding, its simplicity of operation and high efficiency make it one of the most practical processes for further development.

RESISTANCE WELDING

Resistance welding is a joining method that functions by fusion or diffusion bonding of the metals to be joined, utilizing the thermal energy generated by their resistance to the conductance of electricity. This process has a high potential for application to space joining due to two desirable characteristics. One factor pertains to the very short welding energy pulse times that are employed, thus minimizing the time during which hot metal might be exposed to the space vacuum. The second advantage is that the fusion zone is generated in an area which is virtually surrounded by solid metal. This effect thus shields the molten metal from the vacuum. The net effect of these two characteristics is the prevention of problems related to reduced gravity and vacuum and the maximization of thermal efficiency.

Resistance welding for space fabrication is further enhanced by employing a precision dynamically controlled microwelder marketed by Hughes Aircraft Company. The system, set up for opposed electrode spotwelding utilizes an 800 ampere battery pack to achieve square wave rise and decay at a constant welding voltage pulse. Additionally, the Hughes MCW-550 microwelder weighs 65 pounds, complete. A flight model system with the same power output could probably be built to a weight of 30 to 40 pounds. The weight probably could be reduced below 25 pounds for a system utilizing the spacecraft's batteries and charging system. Hughes is presently developing a 2000 ampere system which might significantly enhance the capability of this joining method. The disadvantages of this process are that the faying surfaces must be free of oxides and other contamination, fabrication is restricted to lap joints, and a clamping force must be applied to both sides of the joint or from one side against a rigid backup.

Investigations were initiated in January to evaluate the potential of resistance welding as a joining method for space environment fabrication. All work was conducted with the Hughes MCW-550 microwelder which utilizes a battery pack as the source of pure direct current energy. The unique characteristic of the welder is that it provides constant voltage rather than constant current and thus eliminates overheating during welding which causes metal vaporization (blowouts) and associated detrimental effects. The welder can deliver up to 800 amperes at 1.99 volts which can result in a 16 Kilojoule pulse at the 10,000 millisecond pulse duration.

The first phase of the investigation was to achieve spot welds in the metals of interest to this program. Spot welds were successfully achieved in 321 CRES stainless steel, 6 Al-4V Titanium and René 41 with gages ranging between 0.016 and 0.032 inches. In all instances the weldments were characterized by "nugget" shapes formed from solidification of a "molten plug". Both AZ31 magnesium and 2014 aluminum specimens were sandwiched between two pieces of 304L stainless steel during welding. The effect of this practice was to liberate heat in the two pieces of stainless steel because of their high resisitivity. The metals sandwiched between these sheets were heated by conduction from the steel until their resistance became high enough to generate a significant amount of heat by themselves to achieve fusion. Aluminum welded by this technique resulted in weld-metal expulsion and surface cracking. To develop metallurgically sound joints with aluminum, zinc or an aluminum - 13 wt. percent silicon alloy rolled to 0.003-inch gage were employed as a filler metal. Resistance brazed joints were successful with both filler metals; however, the aluminum alloy provides the advantages of achieving higher joint strength at ambient and elevated temperatures and will not volatilize in the vacuum of outer space. Overlapping resistance spotwelds were similarly achieved for the aforementioned metals employing the same joining techniques. The electrodes employed in the majority of this work were copper or copper-beryllium.

Seam welding was conducted by modification of the equipment to provide for two revolving, cylindrical, copper electrodes. Initial seam welding efforts were conducted on 0.010, 0.020, and 0.030-inch gage 4130 steel sheet. Although most attempts were successful in achieving weldments, they were often characterized by intermittent weld-spots along the surface. It was presumed that this effect was caused by either the copper wheels sticking to the steel sheet or because of discontinuous transmission of current. A 0.001-inch thickness of chromium was plated to the copper wheel contact surfaces to prevent plastic deformation of the copper which had caused it to stick to the base metals. Although this innovation has reduced the intermittent seam welding effect, it has since occurred when chromium plated wheels were employed. Various weld schedules have been attempted to reduce or eliminate intermittent seam weldments. Those schedules that were most successful were with a clamping force ranging from 16 to 20 pounds for most metals welded.

The latest seam weldments were accomplished with 0.020-inch 2014 aluminum, 0.016-inch AZ31 magnesium, 0.020-inch René 41, and 0.020-inch 6Al-4V titanium sheet. Photomacrographs of the weld surface, revealing the seam weld characteristics, and photomicrographs of weld cross sections are presented with the weld schedules employed in Figures 1 through 4. Although the 2014 aluminum weldments were successfully achieved with the 87 wt. percent Al-13 wt. percent Si filler alloy, AZ31 magnesium weldments employing this filler alloy were extremely brittle. Consequently, subsequent magnesium weldments did not utilize the aluminum filler alloy, but were, nonetheless, highly successful as revealed in Figure 2b. Welding of 6Al-4V titanium sheet resulted in incomplete fusion across the joint interface. Because of aluminum's solid solubility in titanium, the aluminum-silicon filler alloy (0.003-inch gage) was employed as a braze alloy. As shown in Figure 3b the joint appears to be successfully brazed. Although the René 41 specimens appeared welded from the surface characteristics, the cross-sections revealed incomplete fusion as illustrated in Figure 4b. This problem was minimized by increasing the clamping force from 12 pounds to 20 pounds. Due to the continuing success achieved with resistance welding of the candidate materials, this fabrication method

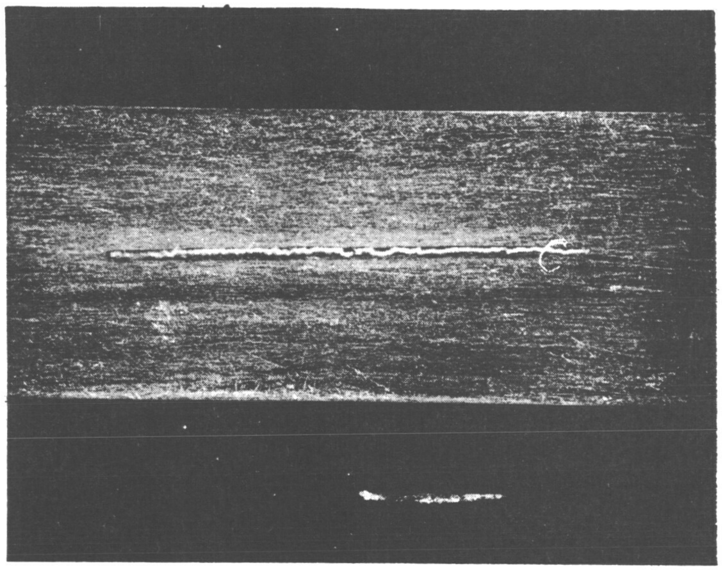


Figure 1a. Seam weld on surface of 2014 Aluminum. Weld schedule: 1.99 volts, 20 lbs. pressure, 30 inches/minute speed. 1.4X

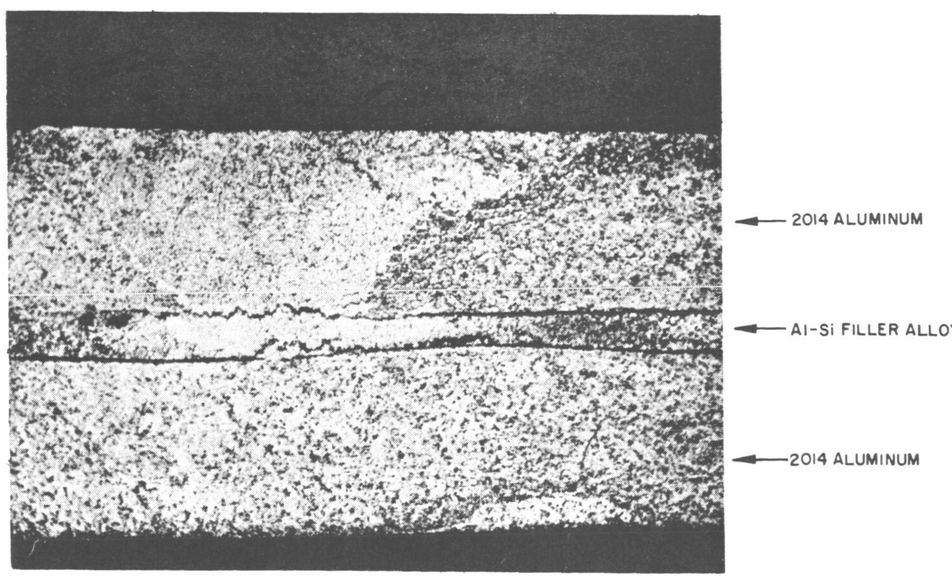


Figure 1b. Photomicrograph of cross-section of 2014 weldment revealing Al-Si Filler Metal brazed to parent metal Etchant: Keller's 50X

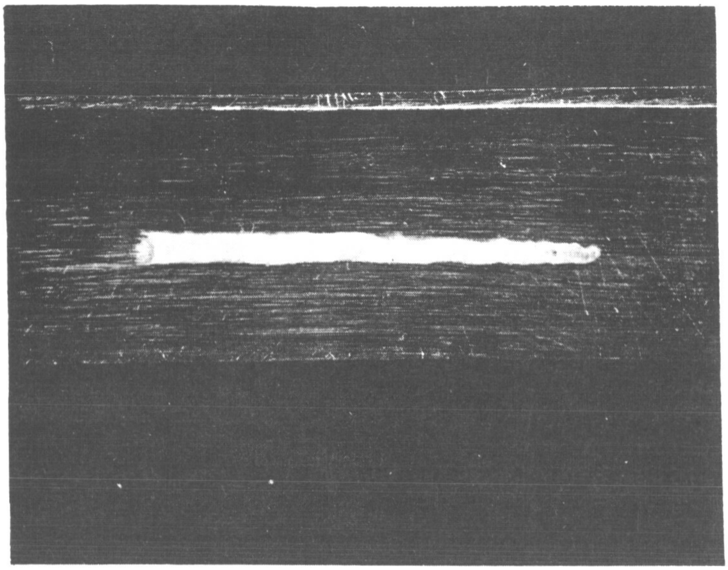


Figure 2a. Photomacrograph of AZ31 Magnesium seam weld. Weld schedule: 1.99 volts, 20 lbs. pressure, 30 inches/minute speed.
1.4X

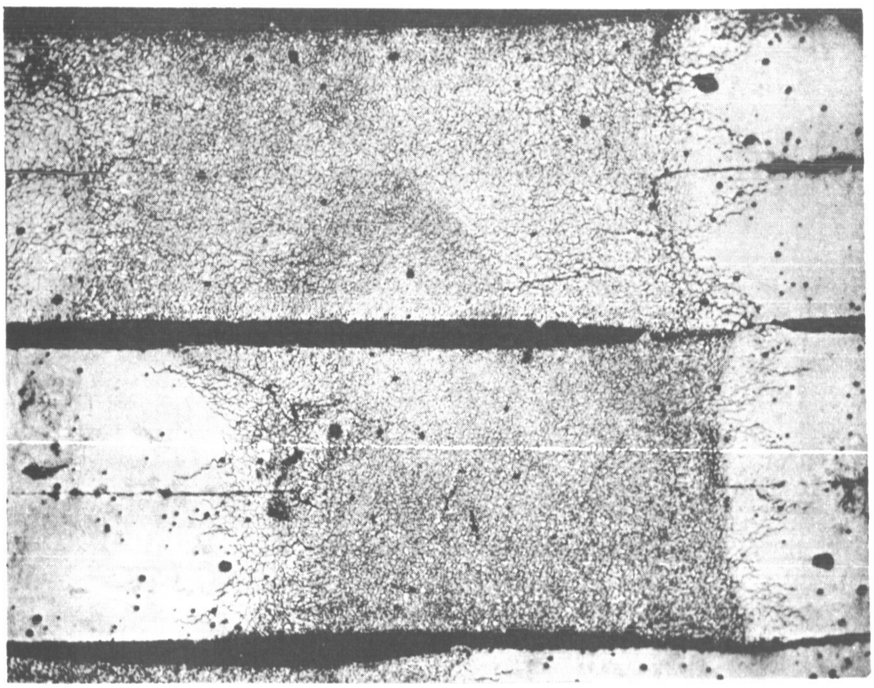


Figure 2b. Photomicrograph of cross-section of AZ31 Magnesium Welds. 10 percent tartaric acid etchant.
50X

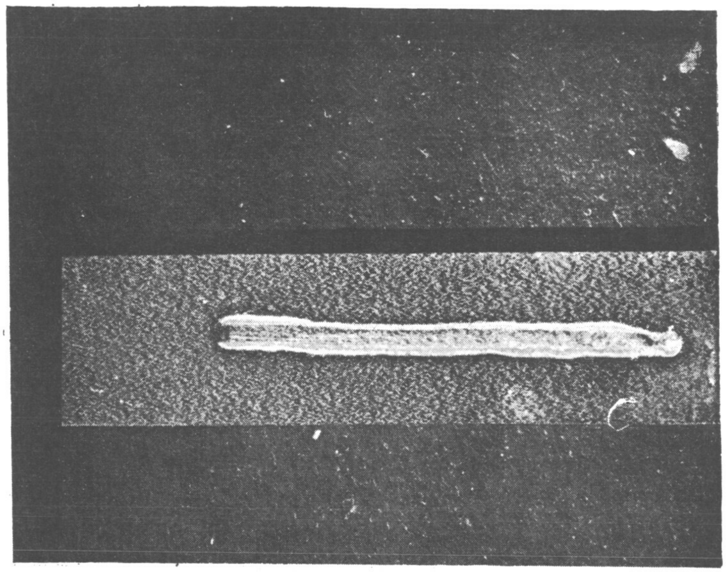


Figure 3a. Photomacrograph of 6Al-4V Titanium seam weld. Weld schedule: 1.99 volts, 20 lbs. pressure, 30 inches/minute speed. 1.4X

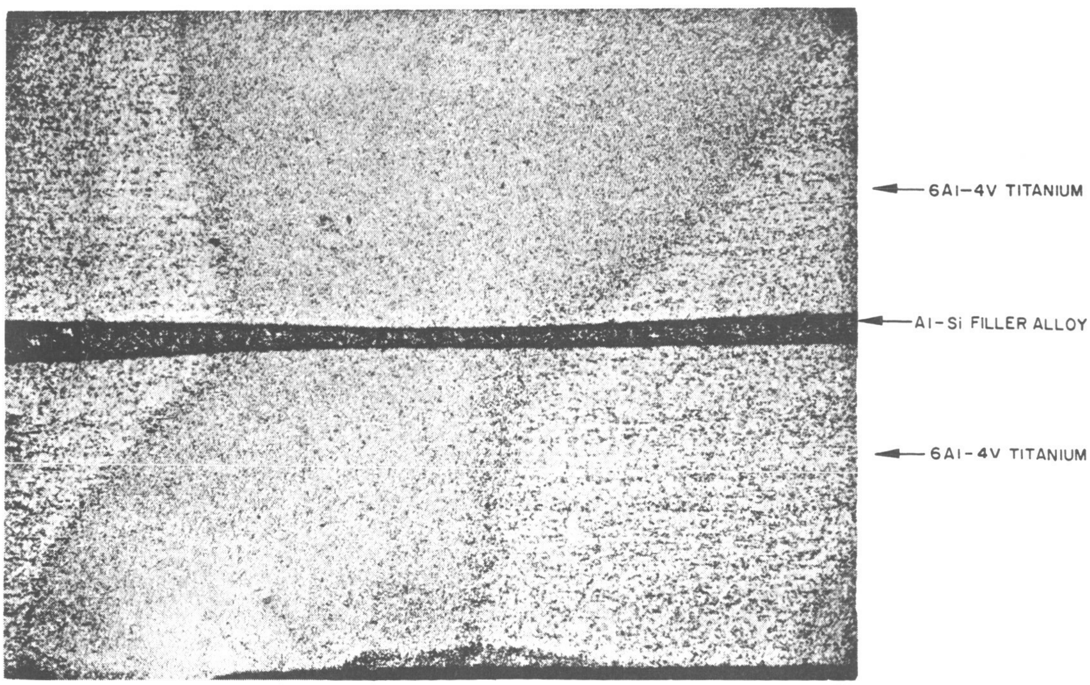


Figure 3b. Photomicrograph of cross-section of 6Al-4V Titanium joint with Al-Si Filler alloy brazed to Titanium. Etchant: 3 percent HF-6 percent HNO_3 bal. H_2O. 80X

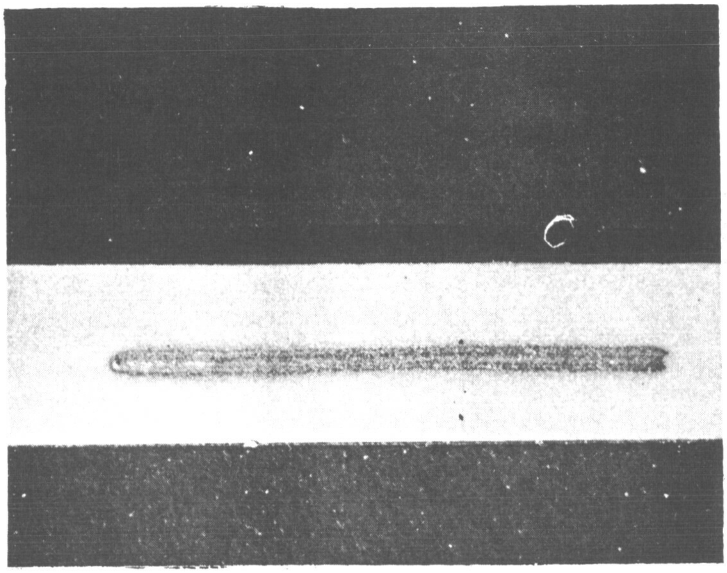


Figure 4a. Photomacrograph revealing René 41 seam weld. Weld schedule: 1.99 volts, 12 lbs. pressure, 30 inches/minute speed. 1X

Figure 4b. Photomicrograph of cross-section of René 41 weld, (Note incomplete fusion of the "nugget" across the joint). 10 percent tartaric electrolytic etch. Etchant: Electrolytic, 10 percent tartaric. 80X

was chosen as one of the two joining techniques for engineering development and test under simulated space conditions.

THERMOCHEMICAL BRAZING

Thermochemical brazing is a joining method which employs exothermic reactants to provide sufficient heat to melt braze filler metal and cause it to wet and bond the adjoining surfaces. Exothermic reactants often are a thermit type composition composed of a metal oxide and a more active metallic reductant such as vanadium pentoxide and boron respectively. The reactants are pre-placed in a position adjacent to the metals to be brazed and ignited by a resistance wire. Often the products of the exothermic reaction can act as a brazing flux when properly placed. Although there are a broad range of reactants available for use in air at ambient pressure, there is only one system that has proven successful in a vacuum. This system utilizes boron and vanadium pentoxide. It is generally blended with some aluminum which attenuates the violence of the reaction but is itself fully oxidized in the process. The reactants are used only to liberate heat. Usually they are isolated from the braze joint and filler alloy by some form of a metal barrier shield which also serves to locate the pieces to be brazed. Cleanliness and tolerance requirements for fit of the components to be joined are as critical for exothermic brazing as for any other brazing process.

From the foregoing information, it is easy to see that exothermic brazing systems must be completely pre-engineered. The reactant blend, quantity of reactants, joint design and fit-up tolerances must all be determined in advance so that field fabrication becomes merely a job of erection, assembly and firing of the exotherm. This would not particularly tax the work capability of an astronaut except if any of the parts were damaged in transit or did not fit exactly. This is a distinct possibility. Further, it would be extremely difficult to engineer a repair kit that would be suitable for all types of damage that are conceivable.

Essentially, the need for thorough pre-engineering means that the system does not allow a sufficient degree of field versatility which would be highly desirable.

The exotherm material is compacted as wafers, discs or pellets which must be heated to a temperature of 800-1000°F by a resistance heated bridgewire before they will ignite. This assures a degree of safety for cabin storage during transit. Because of the nature of the redox reaction involved, there are virtually no fumes, vapors or toxic compounds evolved. About the only vapor emitted during the firing of an exothermic brazing kit is water vapor which comes from water adsorbed on the surface of the pellets and the insulator. This is harmless and can be controlled to some extent by proper vacuum drying and bagging techniques.

No work has been done to evaluate the effect of highly oxidizing atmospheres such as a spacecraft cabin atmosphere upon the ignition, propagation rate and violence or extent of completion of the redox reaction. This area should be investigated if additional work is to be done on exothermic brazing.

Another problem area is the lack of suitable brazing alloys for magnesium or aluminum. No work has been done with exothermic brazing of magnesium either in ambient air or a vacuum. A limited amount of work has been done with some zinc base aluminum brazing alloys with very limited success. NARMCO suggests the use of exothermically cured adhesive systems for these metals.

None of the systems tested have been fired in very hard vacuums. To date, firings have been made at a pre-firing chamber pressure of 10^{-6} torr. The rate of propagation of the reaction at lower pressures would have to be evaluated.

Several tooling concepts were proposed in the NARMCO report. The most promising of these involves a "piano hinge" sort of design. In this design, the sheets to be joined fit together like a piano hinge and a hollow rod containing the exotherm with a braze alloy coating on its outside is inserted as a hinge pin. Firing the exotherm liberates heat which is conducted through the tubing wall and melts the braze alloy, causing it to flow into the hinge joint surrounding it. The concept is reasonable except that it restricts the design of structures and could generate problems with vapor loss of the braze alloy, improper wetting, etc.

NARMCO made a demonstration firing of a tube joint package. Two pieces of 1/2 inch OD stainless tubing were brazed using a close fitting shroud to locate the tubing, hold the brazing alloy and isolate it from the exotherm. An acceptable, leak tight joint was produced although metallographic examination revealed some holidays in the braze.

From the information collated and evaluated on thermochemical brazing it has been determined that this joining technique does not presently provide a high potential for universal application in a space environment for joining of the metals considered in this program. Therefore, further consideration was not given to this joining method.

TUNGSTEN ARC WELDING

Arc welding is a fusion welding process where heat is provided by an electric arc and the materials to be welded may be protected from oxidation by an inert gas. Tungsten arc welding was chosen as a joining technique to be investigated for space fabrication because of its minimal requirements for specialized equipment, low weight and volume. Because of the limited information available on metal-arc welding under reduced environmental pressures, initial work was directed to operation of a tungsten arc in vacuum. It was anticipated that at low pressures a "swelling of the arc" would occur causing the power in the arc to dissipate and the heat input to the workpiece to spread, making the formation of a molten pool difficult.

Laboratory testing was conducted employing a 1/2 cubic foot vacuum chamber, and a Miller Model SR-15GHC DC power cupply with a 1/16 inch diameter tungsten electrode. Vacuum chamber pressures of less than one-inch of mercury were achieved with a large mechanical pump while a DC reverse polarity arc was drawn on the test piece for known periods of time. The objective of these tests was to determine whether a stable arc could be maintained for a long enough period of time to achieve any significant degree of fusion of the base metal. Fifteen to twenty spot weldments were made in AlSl Type 304 stainless steel, titanium and aluminum. Measurements of the electrical parameters of the arc, i.e. voltage, current and time were used to calculate total energy input. The theoretical energy required to achieve the observed amount of fusion was determined by measuring the volume of the fusion zone. The thermal coupling efficiency was then established by determining the ratio of the input energy to that utilized to achieve the weld. The results of this investigation revealed very poor energy utilization and unsatisfactory metallurgical quality of the fused weld spots. These results lead to the conclusion that tungsten arc welding has a low potential for space fabrication applications.

ADHESIVE BONDING

Adhesive bonding provides some attractive features for potential application for outerspace and space cabin environment fabrication. These features include:

a) Fitup tolerances at mating surfaces may be liberal.
b) Dissimilar materials including non-metallics can be joined.
c) Energy sources available in a space environment may be utilized to supply heat for curing or processing bonded joints, e.g. concentrated solar energy.

However, a further evaluation of adhesive bonding has revealed some unattractive features that may limit its application in a space environment. The most serious problem of adhesive bonding for fabrication of space structures involves long curing cycles that may require large quantities of energy. Up to 40-50 kilojoules per inch of bonded joint length may be required to compensate for conductive heat loss in metal structures. Curing cycles may vary from 24 hours at 75°F to one hour at 300°F. The heat sources considered to supply the required heat for curing are solar collectors, electric or thermoelectric sources, and thermal energy from gaseous combustion. Although electric and gaseous combustion do provide a sufficient and continuous supply of energy, solar collectors do not. Solar collectors may provide thermal energy only for periods of time when the bonded structure is exposed to sunlight. Thus the curing time would be limited with solar collector heating. Additionally, rather large, collectors and complex sun tracking equipment may be required to provide enough heat to achieve bonding. A second problem is related to the space vacuum causing outgassing of plasticizers and short chain polymers which could damage adjacent optical equipment and passive thermal control surfaces. Another difficulty that may be anticipated is damage of adhesive bonds by changes in temperature ranging from +250°F to -250°F which would be experienced when the bonded structure was exposed, alternately, to direct sunlight and the darkness of space. Such thermal cycling could cause bond failure from stresses introduced by the differences in thermal expansion of the adhesive and bonded metals.

The aforementioned limitations of adhesive bonding for space structure fabrication indicate a need for further development directed specifically at application in a space environment before it may be considered competitive with alternate joining methods.

EXPLOSIVE WELDING

Explosive welding may be defined as a solid state joining technique where welding is accomplished by plastic flow at the mating surfaces. Metallic bonding is achieved by atom-to-atom contact of the plastically deformed surfaces. The majority of explosive bonding technology has been applied to joining flat plate. Plastic deformation employed to produce bonding is achieved by igniting explosive materials placed on opposite sides of the plates to be joined which creates a high energy shock wave that causes the faying surfaces to be joined under high impact. As illustrated in Figures 5 and 6, the relative positions of

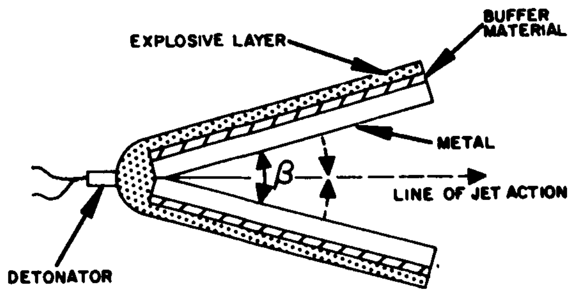


Figure 5. Schematic of angular arrangement of components for explosive welding together flat plate.

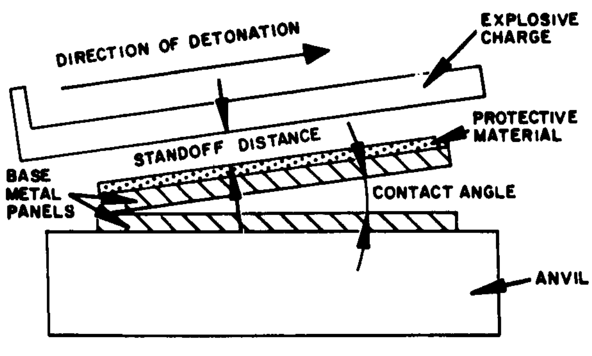


Figure 6. Components of explosive welding setup.

the flat specimens to be joined assume an angle to enable surface films to be extruded in front of the bonding surfaces during welding. Because of this feature, pre-bonding surface cleanliness is not of major significance in attaining metallic bonding. The specific advantages of explosive bonding are: 1) brittle welds between dissimilar metals caused by formation of intermetallic compounds may be eliminated, 2) there is no heat affected zone which would also degrade the material properties. In addition to these advantages, explosive bonding is unique in that the weight penalty versus energy for joining is exceptionally attractive. However, for application in a space cabin or outer space environment, explosive bonding has the disadvantage that weldments other than a flat geometery would probably require rather extensive tooling resulting in an over-all weight penalty. A second and more critical problem is the possibility that the products of combustion would jeopardize the space cabin life support system due to the large quantity of CO_2 that is liberated upon ignition of the explosive. It appears that the disadvantages of the process outweigh its merits.

DIFFUSION BONDING AND PRESSURE WELDING

Diffusion bonding may be defined as a solid state joining technique achieved by simultaneous application of heat and pressure to two well-cleaned metal surfaces. This must be done over a period of time sufficient for atom movement to form a reasonably continuous crystal lattice across the joint interface. Pressure welding is similar to diffusion bonding except that the applied pressure is sufficient to cause plastic flow at the mating surfaces. The plastic flow is sufficient to remove oxide films and allow atomic relocation to vacant lattice sites resulting in the formation of an atomic metal bond to form across the interfaces.

Although these solid state joining processes present attractive features for terrestrial applications, there are serious shortcomings for application to space environment fabrication. One limitation pertains to the requirements for bulky and complex tooling to be employed in space to attain the required pressures for bonding. A second consideration to be scrutinized is the relatively large quantity of heat required to achieve bonding of metals such as titanium and nickel base alloys. These thermal requirements may necessitate large and cumbersome power equipment. A final and important limitation to diffusion bonding in space is that the joints that may be achieved are severely geometry-limited. The majority of bonds accomplished on earth have involved the joining of flat plates; however, tube-to-sleeve joints may be achieved by shrink-fits caused by differences in thermal expansion of the metals employed. Because of the aforementioned problems associated with diffusion bonding and pressure welding for fabrication in a space environment the joining methods were not further investigated.

GAS WELDING

Both fusion welding and brazing may be achieved by the heat of combustion released by burning oxygen and hydrogen. The combustible gases might be obtained from an electrolytic dissociation of water. Combustion can be sustained in a simple oxy-hydrogen gas torch. The chief advantages of this system for space fabrication are its simplicity, and its thermal efficiency realized by 85-90 percent utilization of the electrical energy input as thermal energy available for welding. The water required for generating the fuel gases could be obtained from urine purification. The major space joining problems associated with this system are the fairly high degree of skill and dexterity required for successful welding and the low weld coupling efficiency. Although torch brazing does not require a high degree of skill, problems associated with flux volitization and balling-up of the filler metal may be caused by the extra-terrestrial environment. Preliminary vacuum stability tests of an oxy-hydrogen flame revealed only a lengthening of the flame rather than fanning-out or flaring out.

Initially, a brief research study was conducted to determine the characteristics of an oxy-hydrogen flame in a low pressure environment. Eight combinations of gas pressure and mixture ratios were tested in two replicates. In all tests, flame extinction occurred at a pressure of approximately 2-1/4 to 3-1/4 psia. A literature search determined that for the oxygen-hydrogen system, the minimum ambient pressure which will sustain combustion is about 2 psia. This information correlated well with the experimental results. Subsequent efforts were conducted with a torch design that permitted combustion in a confined chamber at 15 psia and consumed approximately 0.01 standard cubic feet of gas per second.

Design details of the experimental torch which was fabricated for a demonstration of the feasibility of space welding using oxygen and hydrogen gases are shown in Figure 7, a reproduction of HAC drawing number X3031058.

The head consists of a 2.0 inch diameter copper bar with a 0.215 inch diameter hole drilled through it. Two 0.050 inch diameter holes drilled at 45° angles to the 0.215 inch hole are used for feeding oxygen and hydrogen gases into the combustion chamber. A 1/8 inch diameter copper tube was brazed into each of the feed holes to permit coupling to the gas feed system.

Five torch tips were made from standard AN815-4S fittings. Each tip was fitted with an insert made of 347 CRES. The tip inserts varied in size from 0.032 to 0.125 inch diameter.

Ignition of the gases was accomplished by use of a V24-1 miniature spark plug. Power to the spark plug is supplied by a 110 V A.C. transformer.

A 2-1/2 ft x 2 ft x 2 ft vacuum chamber was fabricated for testing the torch. Hydrogen and oxygen gases were supplied from separate "K" bottles. Gases flowed through two calibrated 0-3- PSIG gages. A Brooks flowmeter was placed downstream of the gages but testing showed the flowmeters were unable to accommodate the required volume of the gases. Two Skinner 110 V.A.C. solenoid valves were used as the fire valves. To allow for visual inspection of testing, two plexiglass windows were installed, one at the top and one on the side of the test chamber.

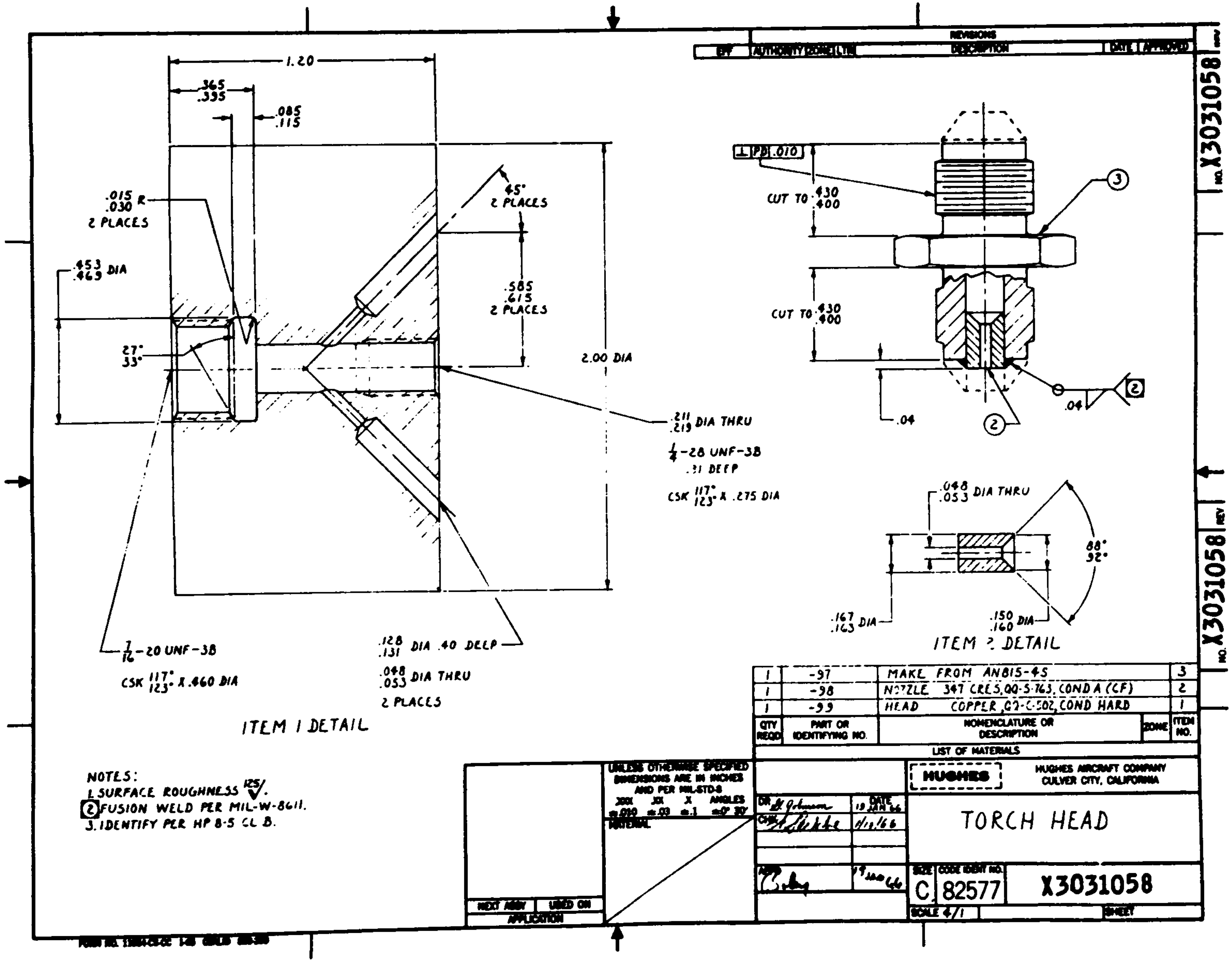


Figure 7. Torch head used for vacuum torch welding studies.

Maximum altitude used for all tests was 100,000 feet, which corresponds to a pressure of about 1/4 psi.

Testing was performed on 2014-T6 and 2219 aluminum sheets. The 2014-T6 sheets were 0.040 inch and 0.250 inch thick. The 2219 was 0.040 inch thick. All targets were approximately 3 in. x 3 in.

Attempts were made at cutting these plates using an 0.050 inch diameter nozzle tip. However, it was determined that not enough heat was liberated to efficiently cut the materials involved. Tests were then performed using tip diameters of 0.078; 0.101 and 0.125 inch. All of these diameters were efficient at cutting all of the materials.

Gas pressures ranged from approximately 0.5 to 10 PSIG for both hydrogen and oxygen. Mixture ratios ranged from 2:1 to approximately 12:1 with 8:1 being the stoichiometric proportion for these gases. All gases, mixtures and pressures ignited without fail with best efficiency obtained using a 0.101 inch or 0.125 inch diameter tip with hydrogen pressure of 3-4 PSIG and oxygen pressure of 0.5-1.5 PSIG. Torch tip to target distances were varied from 1/8 inch to 1 inch. Naturally, the closer the target, the faster was the cutting rate.

Attempts were made at penetration welding various stacks of plates with poor results. Butt welds were obtained with fair fusion. It was believed the inability to successfully weld was caused by extremely high velocity of the exhaust gases. The high exhaust velocity tended to blow the filler rod and the melted parent metal away from the weld zone before they could solidify and achieve the weld. In an effort to decrease the exhaust velocity, an existing torch nozzle was modified to incorporate a shock plate at the nozzle exit plane.

Attempts were made at welding, using various feed pressures and mixture ratios. Various sized holes, ranging from 0.088 inch to 0.140 inch, were drilled in the shock plate in an attempt to obtain optimum exhaust velocity and heating rates. Under all conditions the exhaust velocity was still too great to permit welding. In order to decrease the exhaust velocity the required amount, a further nozzle expansion downstream of the shock plate would be required. However, the expansion required would be too great to allow a suitably localized flame point for welding.

Platinum black was than deposited on a porous, sintered stainless steel disc approximately 2.5 inches in diameter. The platinum black acted as a catalytic ignition source in place of the previously used spark plug. Platinum black was then deposited on 3 porous sintered nickel plugs 0.5 inch in diameter. These were tested to ascertain their ability to act as a velocity decreasing device and as partial flame retainers.

Gas pressures ranged from 3-20 psig for both hydrogen and oxygen with volumetric mixture ratios ranging from 2:1 to 8:1. Of the three plugs tested, two failed to cause ignition under any circumstances. The remaining plug caused ignition after approximately 30 seconds of gas flow and gas pressures of 20 psig oxygen and 10 psig hydrogen. The upstream side of the plug was burned and the downstream side indicated a very slight erosion had started due, perhaps, to the flame stabilizing on the face of the plug.

The platinum black was deposited on the porous plugs in various degrees of thickness. Both the thickest and thinnest deposited surfaces failed to cause ignition, whereas the medium thickness surface deposits did allow ignition to occur. The thin surface was probably not sufficiently active and the thick surface may have blinded the porous plug.

Extensive effort would be required to develop and test an efficient catalyst system which could also be used as an exhaust velocity depressant. Because of this problem, and the high degree of operator skill required, this joining technique was not further pursued.

FOCUSED SUNLIGHT JOINING

Because of the availability of solar energy in outer space, focused sunlight as a space fabrication technique has been given serious consideration. To achieve maximum utilization of solar energy for joining, primary transducers may be used to concentrate solar energy into a beam for direct heating. The type, size and shape of the solar concentrator chosen would require a trade-off between total energy required and the area of the material to be heated. As the aperature of the concentrator is increased, the size of the region being heated is increased for a given f-ratio. Solar concentrators provide the advantage of being light and portable but are best suited for use external to the spacecraft. Although there is no convenient way to design a truly portable system for fabrication within the spacecraft, a solar concentrator might be affixed to the exterior of the vehicle with a window provided to accomplish benchwork inside the cabin.

Diffusion bonding and fusion welding of aluminum or magnesium may be accomplished with a 50X solar concentrator if the metal surfaces are given a thermal control coating having a minimum α/ϵ ratio of 10. Brazing, conducted with solar energy, would be feasible where the concentrator was capable of supplying sufficient energy to melt the filler alloy. Consequently, solar energy brazing of aluminum and magnesium would be feasible since sufficient energy would be available to to melt the braze alloys employed. However, temperature control problems could be anticipated. Titanium and nickel base alloys would not be as amenable to solar energy brazing due to the much higher energy required to melt their braze alloys.

Solar concentrators could be used for adhesive bonding where the solar energy may be utilized to cure one part epoxy adhesive systems through the use of controlled absorptivity material coated tapes. As an example, precoated faying surfaces could be brought together, clamped in position and cured by solar heat induced by a highly absorptive tape. The tape could be removed or left in place after the adhesive has cured.

The primary disadvantage of the utilization of solar energy for this joining system is that sunlight will not be available for extended periods of time to meet curing time requirements. Consequently, for solar energy to be adopted to supply heat for relatively long periods of time would involve methods of "tracking" the sun during fabrication of the space vehicle. Development of such a "solar tracking system" may prove to be very complicated.

Although focused sunlight joining for space environment fabrication does possess potential, (particularly for adhesive bonding), difficulty would be encountered in metallurgical joining of metals and alloys with high melting points. Since other fabrication methods being explored, e.g., electron beam and resistance welding, possess over-all higher potential for joining of metals in space, solar energy joining has received less attention in this program and was not further evaluated.

LASER WELDING

Extensive research in the field of laser welding has been performed at Hughes. Most of this work has been directed toward achieving an understanding of the fundamental principles underlying the transfer of energy from the light wave emitted by the laser to the surface of the target workpiece in which thermal work is performed.

In general, there are several major drawbacks to the use of laser welding as a space repair and fabrication technique. First of all, laser systems with a sufficiently high power output to do useful metallurgical work are all pulsed output devices. It has been found at Hughes that short pulse lengths tend to vaporize the target rather than melt it. The pulse must be stretched out to at least 2-1/2 - 3 milliseconds duration if successful penetration of fusion is to be obtained. The longer the pulse duration is, the better the weld. If high power can be coupled with a long pulse, then defocussed beams can be used to make fairly good welds of a useful size and depth of penetration. Unfortunately, the conditions of long pulse duration and high optical power output are not easily attainable and certainly are not consistent with lightweight flight type hardware.

To obtain a long pulse, an inductive-capacitive pulse forming network must be used. Unfortunately, as the pulse length is stretched beyond, say, six or eight milliseconds, the inductive reactance in the power supply circuit begins to get high enough to severely limit the power output and cause severe heat dissipation problems in the power supply. Obviously, the power supply becomes very heavy and bulky.

This brings up the second significant problem. The pulsed laser is basically an inefficient device from an electrical energy utilization standpoint. Excellent thermal coupling is readily obtained. That is, a very high proportion of the energy in the optical beam emitted by the laser is converted to useful metallurgical work. However, there are high dissipation losses in the best power supplies available and an enormously inefficient optical coupling between the pumping source (usually a Xenon flash lamp) and the resonant cavity (the ruby rod). The reason for this is that the ruby is excited only by a particular wavelength of the "noisy" white light used for pumping. The remainder of the optical energy represented by the rest of the spectral wavelengths must be dissipated as heat in the reflector system in which the resonator is mounted. Unfortunately, the problem becomes even worse because the efficiency of the resonator drops off sharply as its temperature increases. External cooling with dry nitrogen gas, water or liquid nitrogen may be used to alleviate this problem but the best efficiency obtained is still of the order of magnitude of a few hundredths to perhaps a few tenths of a percent.

The third major problem involves the basic physical properties of the metals to be welded. The best results have been obtained with metals having a high thermal diffusivity, such as copper and aluminum. Metals such as stainless steel and titanium tend to confine or restrict the flow of heat thereby increasing the likelihood of vaporizing rather than merely melting.

Associated with these problem areas and further complicating the potential applications of laser welding is the fact that seams must be welded by the overlapping spot technique. This requires, perhaps twenty-five to seventy-five spots per lineal inch of seam. It is, therefore, a slow and tedious process and requires high precision tracking equipment to locate the overlaps accurately. Furthermore, if any one of the spots accidentally burns through the stock, salvage repair would be extremely difficult.

There is some hope for the future of laser welding. The Hughes Research Laboratories and Bell Laboratories have both succeeded in making a ruby laser operate in a continuous mode but at very low power levels. Recent developments indicate the possibility exists of developing a continuous operating gas laser with an output of the order of magnitude of hundreds of watts. This type of device will make laser welding a reality.

EVALUATION OF ENERGY SYSTEMS

Upon the choice of a joining method for space environment fabrication, the power requirements for its successful utilization must be determined. Consequently, those power systems that seem to provide capability for adaptation to the chosen joining method shall be evaluated. As a result of preliminary studies, the following candidate energy systems were studied:

NUCLEAR REACTOR SYSTEMS

Nuclear fission represents an excellent source of energy, and a large amount of effort is being spent by other contractors in developing space power systems using compact fission reactors as heat sources. In order to minimize shielding weight, however, shadow shields are almost always specified in such power systems. While shadow shielding may be quite adequate for inanimate payloads, its use is highly questionable for operations involving men engaged in building a structure in space or on the moon. It appears, therefore, that nuclear reactor power systems for manned operations in space will require much more shielding than is usually allowed in their designs.

Nuclear power systems will afford a high flexibility in power management including high peak demand and overall power. However, development of such systems is not far enough along that they can be considered as practical power sources within the immediately forseeable future.

SOLAR CELL/BATTERY SYSTEMS

Solar energy has the attractive features of providing a high power flux density (the solar constant of one AU is 0. 14 watts/cm^2) and of having been successfully exploited. It is one of the most attractive sources of power for space operations. Figure 8 illustrates a block diagram of suitable solar energy conversion systems.

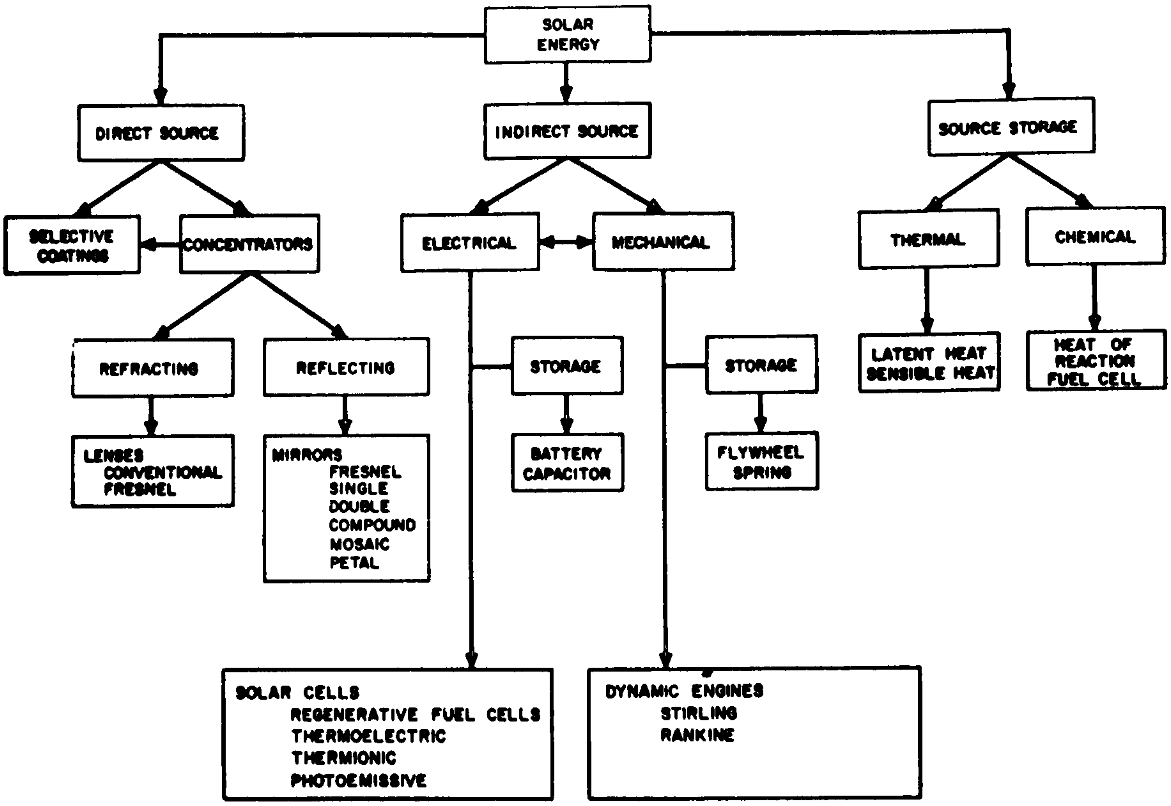


Figure 8. Solar Systems Diagram

A direct thermal system may consist of several transducers, depending on heating requirements. The unconcentrated solar flux at 1 AU will raise the temperature of an aluminum sphere to a value no higher than about 200°F (equilibrium, assuming a uniform temperature). If higher temperatures are desired, then either a selective surface coating or a concentrator may be used. A selective coating of α/ϵ equal to 10 would raise the temperature to a value no higher than 500°F. A solar concentrator which increases the solar constant by a factor of 50 would melt the aforementioned aluminum sphere, provided the hot spot covered the exposed side of the sphere completely. If the size of the hot spot is small relative to the dimensions of the work being heated, then the heat losses due to conduction and radiation will tend to limit the maximum temperatures attainable. Solar concentrators may be the most versatile transducer for joining methods requiring direct heating to temperatures below the melting point of aluminum. Thus, they would be desirable for melting soft solders or curing adhesives. The various types of refracting and reflecting solar concentrators which could be used are shown in Figure 9.

One of the major disadvantages of direct solar systems is the necessity of maintaining a direct line of sight between the solar collector, the sun and the workpiece. This imposes a requirement for a solar tracking system and limits the time during which work can be performed to those periods when the sun is in a favorable orientation.

The use of solar cells and batteries minimizes the problem of sun-orientation but has the disadvantage of the additional weight imposed by the energy storage system. While batteries are heavy, they do have the advantage of providing pure d c power and possess a known reliability.

FUEL CELL SYSTEMS

Chemical storage derives its feasibility from the fact that electromagnetic energy or heat may trigger or accelerate certain chemical reactions. Once the source is removed, the reaction may proceed in the other direction giving back heat or electricity. A good example of the latter is the regenerative fuel cell.

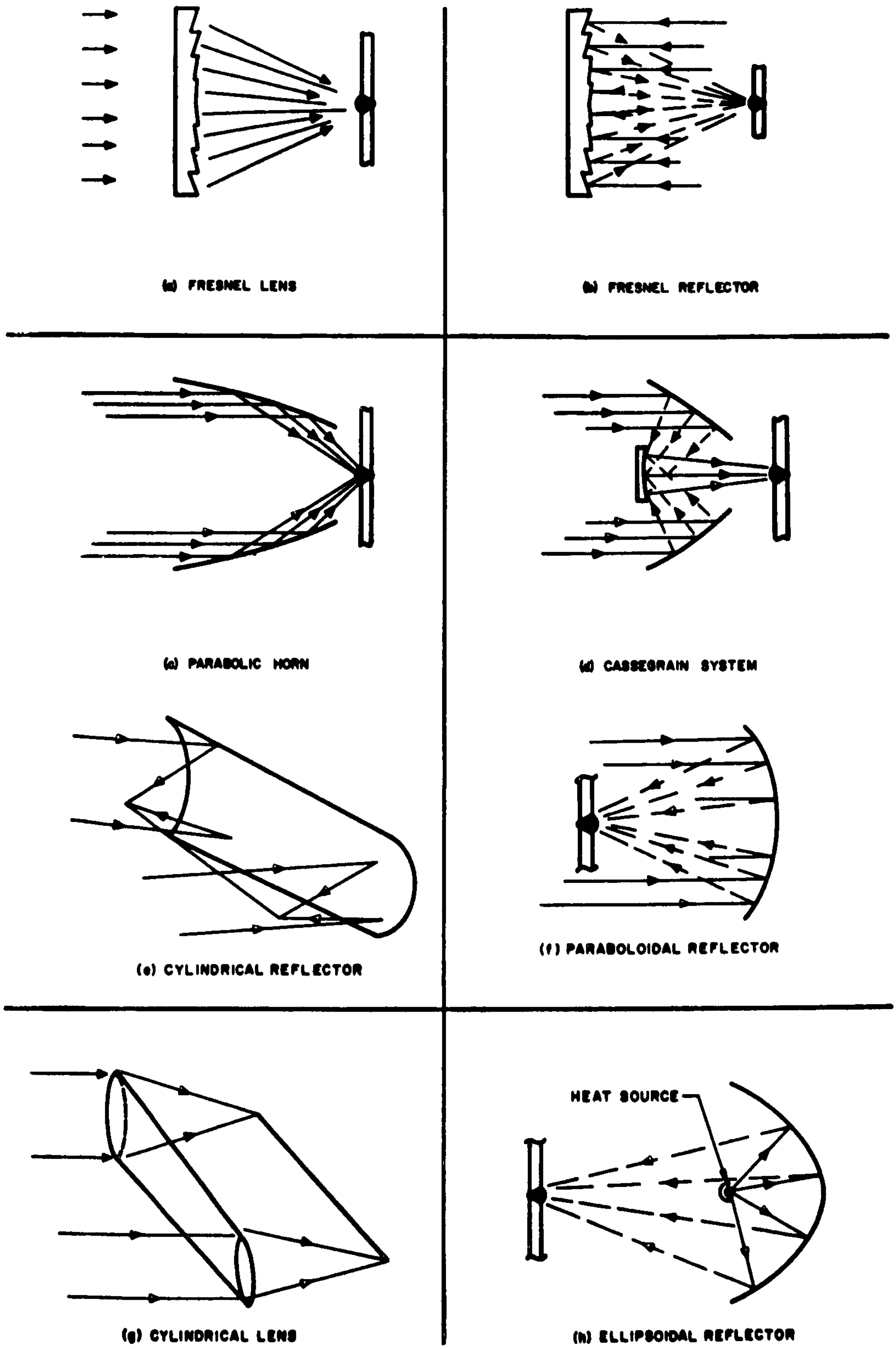


Figure 9. Types of solar concentrators.

A fuel cell may be defined as an electrochemical conversion device which delivers direct current as the result of oxidation of a flowing fuel. As such, the fuel cell differs from the conventional battery only in the manner in which the chemical energy source is introduced. As indicated in Figure 10, fuel cell systems are capable of more energy storage per pound than conventional batteries. For high performance applications, the hydrogen-oxygen family of fuel cells appears to be the most promising type. The electrolysis of water through the aid of photovoltaic cells and subsequent use of the hydrogen and oxygen in a regenerative fuel cell has been suggested.

A typical fuel cell power pack being developed for field use weighs 30 pounds and produces 200 watts for 14 hours on a 6-pound canister of fuel (hydrogen from decomposition of a metal hydride). The oxidizer is oxygen from the life support system. This unit exemplifies the feasibility of fuel cells as a convenient portable energy source. For operation outside a habitable atmosphere, of course, the oxygen would also have to be supplied.

For high power levels (megawatts), fuel cell systems tend to become rather bulky as well as heavy, although they are efficient devices for energy conversion.

Another characteristic of fuel cells is the relatively inflexible current density available from a given cell. This tends to limit their usefulness in applications requiring occasional surges in power supply. Conventional batteries are more flexible in this respect than fuel cells.

It is our understanding that fuel cell power systems similar to those in the Gemini vehicles will be used in Apollo and other contemplated programs in which metal joining equipment may be used. Power demand for a joining system may be of the order of magnitude of 1.5 to 2.0 kw. It is assumed that the voltage-current characteristics of fuel cell systems could be adjusted with appropriate switchgear to make the appropriate series or parallel interconnections of cells that may be required.

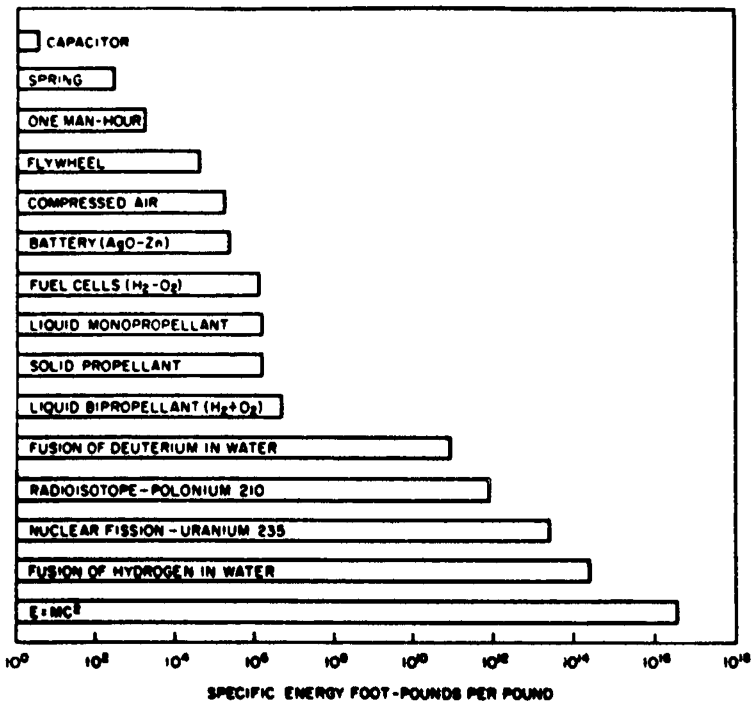


Figure 10. Performance characteristics of 5-cell series solar module.

RECOMMENDATION OF TWO PROCESSES FOR FEASIBILITY DEMONSTRATION

It was recommended that resistance and electron beam welding be developed as joining processes for extraterrestrial fabrication and repair of space vehicles. Examination of Table 2 reveals that these joining processes provide the largest number of advantages for application in a space environment. Resistance welding appeared to have the best potential as realized by such pertinent factors as its operational simplicity, reliability, minimum joint preparation and tooling, and safety. Electron beam welding also exhibits attractive features for space joining which include excellent joint strength and reliability, minimal operator skills, and a high natural adaptability to the space environment, e. g. zero gravity, and low pressures. The only pertinent disadvantage of resistance welding was the thickness limitation of weldments achieved with 6Al-4V-titanium and Inconel 718. A possible solution to this problem was demonstrated through the use of low melting filler materials. The disadvantages related to electron beam welding for space fabrication are realized in relatively complex tooling, close tolerances, volume and weight requirements associated with high power source requirements, and possible safety hazards.

	Joint Characteristics						Reliability		Power			
										Type of		
Joining Process	Thickness Limitation	Joint Configuration	Filler Required	Material Limitation	Strength/ Unit Length of Joint	Leak Tight	Joint Strength Consistency	Operator Skills Required	Required/ Unit Length of Joint	Elec-trical	Mechan-ical	
1) Gas Welding	No	Butts, Laps, Fillets	Probably	No	Poor	?	Poor to Fair	Yes, High	? (High but packs well)			
2) Electron Beam Welding	No	Butts, Laps	No	No	Very good, 60-100% of parent metal	Yes	Very Good	No (can be highly auto-mated)	Dependent on mate-rial, order of magni-tude in 1-10 K_j/ in. range	√		
3) Arc Welding	No	Butts, Fillets	In some cases	No	Fair to Good	Yes	Fair to Good	Yes, Fairly High	Dependent on mate-rial, order of magni-tude 2-20 K_j/in.	√		
4) Laser Welding	Yes very light gage (0.01-0.02)	Butts best, some Fillets	No	Yes, not good on on highly reflective or low cond.	Probably Good?	? Probably No	?	No	Very high	√		
5) Resistance Welding	(?) Yes, light to med. gages 0.060 "max."	Laps only	In some cases	No (use filler with Al, Mg)	Probably Good	Yes	Probably Good	No	Medium depends on material 1-5 K_j/in.	√		
6) Diffusion Bonding	No	Most likely Laps or Tees, maybe Butts	No per-haps in rare cases	Perhaps. Works best with soft duc-tile metals	Fair to Good	Probably Yes	Poor to Fair	No - but high order of planning and judge-ment req'd	Moderate to high	Second-dary √	Primary √	S c
7) Explosive or Pressure Welding	No	Laps, Tees maybe Butts	Gener-ally No	Perhaps. Works best with soft duc-tile metals	Probably only Fair	Probably Yes	Poor to Fair	No - but high order of planning and judge-ment req'd	? (High but packs well)		Chemic	
8) Adhesive Bonding	No	Laps	Yes (The adhesive)	Yes - Dependent primarily on service tempera-ture	Low	Perhaps	Fair	Minimal	Could be high (due to conduc-tive heat losses)	Possi-bly √		I t
9) Focused Sunlight Joining	Probably	Laps, Fillets	In most cases	Not if Filler used	Probably only Fair	Probably Yes	Fair to Good	Yes, Orienta-tion of reflector critical	Low			
10) Thermo-chemical Brazing	No	Laps	Yes	Yes - Not good for Al, Mg	Fair to Good	Probably Yes	Fair to Good	No	Low	√		
11) Cold Molecular Welding	No	Butts, Laps, Tees	No	Perhaps. Works best with soft, duc-tile metals	Poor	Probably Yes	Poor to Fair	No - but high order of planning judge-ment req'd	Low to moderate		√	

equirements				Joint Preparation				System Characteristics			
ower											
Gas	Sunlight	System Efficiency	Demand/ Unit Time	Cleaning Required	Tooling Required	Tolerances Required	Set-up Problems	Total Volume	Total Weight	Develop- ment Cost	Production Cost
√		Low	-	-	Minimal	Minimal Required	No	Low	Low	Low	Low
		High	KW range	Yes	High	Close, 0.001 to 0.005" fit-up	Yes, tool- ing and auto-head alignment	High sev- eral ft^3	High sev- eral cwt	High	High
		Poor to Fair	KW range	Yes	Fair to High	Fair 0.010" to 0.020" fit-up	No (Tool- ing)	Low	Low	High	Low
		Very Poor	? Watt range	Probably No	High	Close, 0.001 to 0.005 fit-up	Yes, tracking difficulties envisioned	Very high	Very high	Very high	Medium
		Good	Low KW range	Minimal	Minimal	Reasonable fit-up OK (Laps)	Minimal	Low	Low	Low	Low
econd- ary √	Second- dary √	Low	Low	Must be carefully cleaned	Very High	Fair Dependson joint	Yes, Tool- ing	High tool- ing volume	High tooling weight	Low	Depends on tooling (could be high)
al		-	-	No	Fair to High	Moderate	Yes, Tool- ing	Tooling high, explosive low	Tooling high, explosive low	Moderate	Depends on tooling
ossi- ly √	Possi- bly √	Probably Low	Probably Low	Yes	Fair to High	Moderate	Yes, Tool- ing	Tooling could be high	Tooling could be heavy	Low	Depends on tooling
	√	-	-	Probably Yes	Fair to High	Close, 0.001 - 0.003" fit-up	Yes, Tool- ing	Probably High	Probably Heavy	High	Moderate to high dependent on tooling
		Good	Negligible	No	? Simple to complex	Close, 0.001 - 0.003" fit-up	Possible tooling problems	Dependent primarily on tooling	Dependent primarily on tooling	Moderate (except for Al and Mg)	Moderate
		-	-	Must be carefully cleaned	High	Depends on joint design	Yes, Tool- ing	Fair to High	Probably High	Moderate	Depends on tooling

	Space Environmental Requirements					Human Factors				
Logistic Problems	Metal Loss in Vacuum	Metal Oxication in Spacecraft	Suitable for Zero Gravity	Thrust Prob-lems	Torque Prob-lems	Radiation Hazard	Shock Hazard	Explosion Hazard	Operational Simplicity	Thrust Reaction
Minimal	Yes, Dependent on skill	Yes, Hazardous	No	Yes	No	No	No	Yes	Low (com-plex)	Yes
High power required	Minimized by high welding speed	Possible hazard	Yes	No	No	Maybe X-ray	Yes	No	Fair to Good	No
High power required	Yes	Yes Harardous	No (Depen-dent on Tooling)	No	No	Some UV	Moder-ate	No	Low (skill dependent)	No
Power required ?	Minimal	Minimal	Yes	No	No	Not Parti-cularly	Possi-bly	No	Poor	No
Minimal	None	None	Yes	No	Some	No	Minimal	No	Very Good	No
Minimal	None	None	Yes	No	Yes	No	No	No	Good-requires planning and judgement	No
Minimal	None	None	Yes	Yes	No	No	No	Extreme	Good	Yes
Could be high power required	None	None	Yes	No	No	No	No	No	Fair	No
Minimal	None	Minimal	Yes	No	No	Some UV	No	No	Low to Fair	No
Minimal	None	None	Yes	No	No	No	No	Maybe?	Fair to Good (dep (depends on tooling)	No
Minimal	None	None	Yes	No	Some	No	No	No	Fair	No

Table 2. Summary sheet, joining process characteristics.

FEASIBILITY DEMONSTRATION

The feasibility demonstration phase of this program has involved the preparation and testing of samples of a number of different gage thicknesses of several common structural materials. Joining was performed under conditions approximating those prevailing in an extra-terrestrial environment. The samples were tested at various ambient temperatures to obtain meaningful engineering data. The test materials and gage thicknesses used for this evaluation study are summarized in Table 3. In all cases materials were procured from commercial vendors in accordance with the appropriate Military, Federal or AMS specifications.

Electron beam welded test specimens were prepared by butt welding panels together in a suitable welding fixture. The resultant panels were subjected to visual, dye penetrant and radiographic inspection prior to machining them into test specimens. The test specimens were of a design basically conforming to the specified requirements of the Type F2 specimen, Federal Test Method Standard 151, Method 211.1. Tensile tests were performed in accordance with ASTM procedure E-8 at +250°F, +70°F, -100°F and -320°F. This latter test temperature is some 70°F lower than originally proposed but was used as a safe, reliable, expedient solution to cryogenic testing problems. The use of liquid nitrogen was deemed far safer in the test laboratory than the use of liquid air because of fractionation of liquid air which would result in a dangerous increase in the oxygen concentration of the liquid air. Furthermore, testing specimens totally immersed in liquid nitrogen assured reliable test temperature control.

The resistance welded/brazed/soldered samples were all prepared as lap shear type specimens. Specimen design was again based upon the F2 design of Federal Test Method Standard 151, Method 211.1. The testing procedure was identical to that used for the electron beam welded specimens.

Material	Gage Thicknesses, inches
2014 Aluminum	0.012, 0.020, 0.032
AZ31B Magnesium	0.063, 0.072, 0.082
6Al-4V-Titanium	0.036, 0.072, 0.090
Inconel 718	0.043, 0.078, 0.125

Table 3. Test materials and gage thicknesses.

Another significant difference between the two test practices was that the resistance welded/brazed/soldered specimens were fully machined (in halves) prior to joining and were processed as individual specimens. They were visually inspected but were not subjected to radiography because it was felt such tests would not be particularly meaningful.

Subsequent sections of this report describe the specific practices, problems and test results for the two joining methods under evaluation.

ELECTRON BEAM WELDING

Test plates of all of the required materials and gages were welded using the weld schedules summarized in Table 4. These schedules were predicated upon information developed in earlier phases of this program in which depth of penetration was evaluated as a function of beam power. The weld schedules were modified only slightly, as required to obtain satisfactory joints, by changing welding speed or focus. In general, an attempt was made to weld at low accelerating voltages and the total welding power was held below one kilowatt in all cases. This is of significance since one of the original bogies for any joining system was that the power used should not exceed 1800 watts. These tests generally establish the feasibility of electron beam welding from an electrical power management standpoint.

Three serious problems were encountered in welding the magnesium, the lightest gage aluminum and the Inconel 718/6Al-4V-titanium test plates. The Inconel 718/6Al-4V-titanium joint system is, in all probability, not weldable by fusion welding techniques. The magnesium joint system is practical for structural joints but probably cannot be used for hermetic sealing. The light gage aluminum joint system is impractical unless special tooling or joint design concepts are utilized. Each of the materials combinations will be discussed separately.

MAGNESIUM

A full penetration weld could not be obtained by welding from one side only, because of the tendency of the magnesium alloy to vaporize and cause arcing in the electron gun. Therefore, the sample plates were welded from both sides in order to obtain samples for mechanical testing. Even with this practice, the magnesium alloy plates contained numerous pit-type defects in the weld beads as shown in Figure 11. These defects were caused by vaporization of the alloy during welding. This is a particularly bothersome problem since it tends to be self-compounding.

Material	2014 Aluminum	2014 Aluminum	2014 Aluminum
Gage thickness	0.012 inch	0.020 inch	0.032 inch
Emitter/cathode distance	0.357 inch	0.347 inch	0.357 inch
Cathode size	0.160 inch diameter	0.160 inch diameter	0.160 inch diameter
Cathode/anode spacer	0.850 inch	0.750 inch	0.200 inch
Accelerating voltage	15 KV	20 KV	20 KV
Beam current	10 ma	12 ma	12 ma
Power	150 watts	240 watts	240 watts
Welding speed	80 ipm	80 ipm	20 ipm
Specific energy	112.5 j/inch	180 j/inch	720 j/inch
Focal length	2 inches	2 inches	2 inches
Focus current	3.4 amperes	3.9 amperes	3.9 amperes
Material	**AZ31B Magnesium**	**AZ31B Magnesium**	**AZ31B Magnesium**
Gage thickness	0.063 inch	0.072 inch	0.082 inch
Emitter/cathode distance	0.357 inch	0.357 inch	0.357 inch
Cathode size	0.160 inch diameter	0.160 inch diameter	0.160 inch diameter
Cathode/anode spacer	0.850 inch	0.850 inch	0.850 inch
Accelerating voltage	20 KV	20 KV	20 KV
Beam current	15 ma	15 ma	15 ma
Power	300 watts	300 watts	300 watts
Welding speed	60 ipm	60 ipm	60 ipm
Specific energy	300 j/inch	300 j/inch	300 j/inch
Focal length	2 inches	2 inches	2 inches
Focus current	3.9 amperes	3.9 amperes	3.9 amperes

Table 4. Electron beam welding conditions.

Material	6Al-4V-Titanium	6Al-4V-Titanium	6Al-4V-Titanium
Gage thickness	0.032 inch	0.066 inch	0.090 inch
Emitter/cathode distance	0.347 inch	0.347 inch	0.347 inch
Cathode size	0.160 inch diameter	0.160 inch diameter	0.160 inch diameter
Cathode/anode spacer	1.400 inches	0.300 inch	0.100 inch
Accelerating voltage	20 KV	20 KV	20 KV
Beam current	15 ma	30 ma	45 ma
Power	300 watts	600 watts	900 watts
Welding speed	15 ipm	50 ipm	60 ipm
Specific energy	1200 j/inch	720 j/inch	900 j/inch
Focal length	2 inches	2 inches	2 inches
Focus current	3.9 amperes	3.9 amperes	3.9 amperes
Material	**Inconel 718**	**Inconel 718**	**Inconel 718**
Gage thickness	0.043 inch	0.078 inch	0.125 inch
Emitter/cathode distance	0.347 inch	0.347 inch	0.347 inch
Cathode size	0.160 inch diameter	0.160 inch diameter	0.160 inch diameter
Cathode/anode spacer	0.650 inch	0.300 inch	0.100 inch
Accelerating voltage	20 KV	20 KV	20 KV
Beam current	20 ma	30 ma	45 ma
Power	400 watts	600 watts	900 watts
Welding speed	20 ipm	15 ipm	20 ipm
Specific energy	1200 j/inch	2400 j/inch	2700 j/inch
Focal length	2 inches	2 inches	2 inches
Focus current	3.9 amperes	3.9 amperes	3.9 amperes

Table 4 (Continued). Electron beam welding conditions.

Material	Inconel 718/ 6Al-4V-Titanium	Inconel 718/ 6Al-4V-Titanium	Inconel 718/ 6Al-4V-Titanium
Gage thickness	0.043 inch/ 0.036 inch	0.078 inch/ 0.072 inch	0.125 inch/ 0.090 inch
Emitter/cathode distance	0.347 inch	0.347 inch	0.347 inch
Cathode size	0.160 inch diameter	0.160 inch diameter	0.160 inch diameter
Cathode/anode spacer	1.400 inches	0.300 inch	0.100 inch
Accelerating voltage	20 KV	20 KV	20 KV
Beam current	14 ma	30 ma	45 ma
Power	300 watts	600 watts	900 watts
Welding speed	15 ipm	50 ipm	20 ipm
Specific energy	1200 j/inch	720 j/inch	2700 j/inch
Focal length	2 inches	2 inches	2 inches
Focus current	3.9 amperes	3.9 amperes	3.9 amperes

Table 4.(Continued). Electron beam welding conditions.

The vaporized metal generally gets into the electron gun where it causes arcing. As an arc is drawn between the various components of the electron gun, current surges occur which, in turn, cause the localized heating that appears as vaporization pits in the weld bead. Thus, the problem

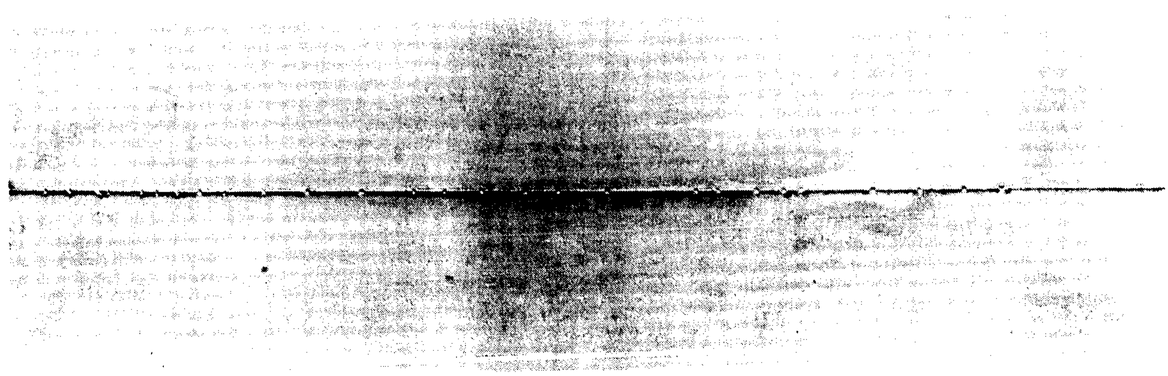


Figure 11. Electron beam welded magnesium plate revealing pit-type defects in weld bead. (R112573)

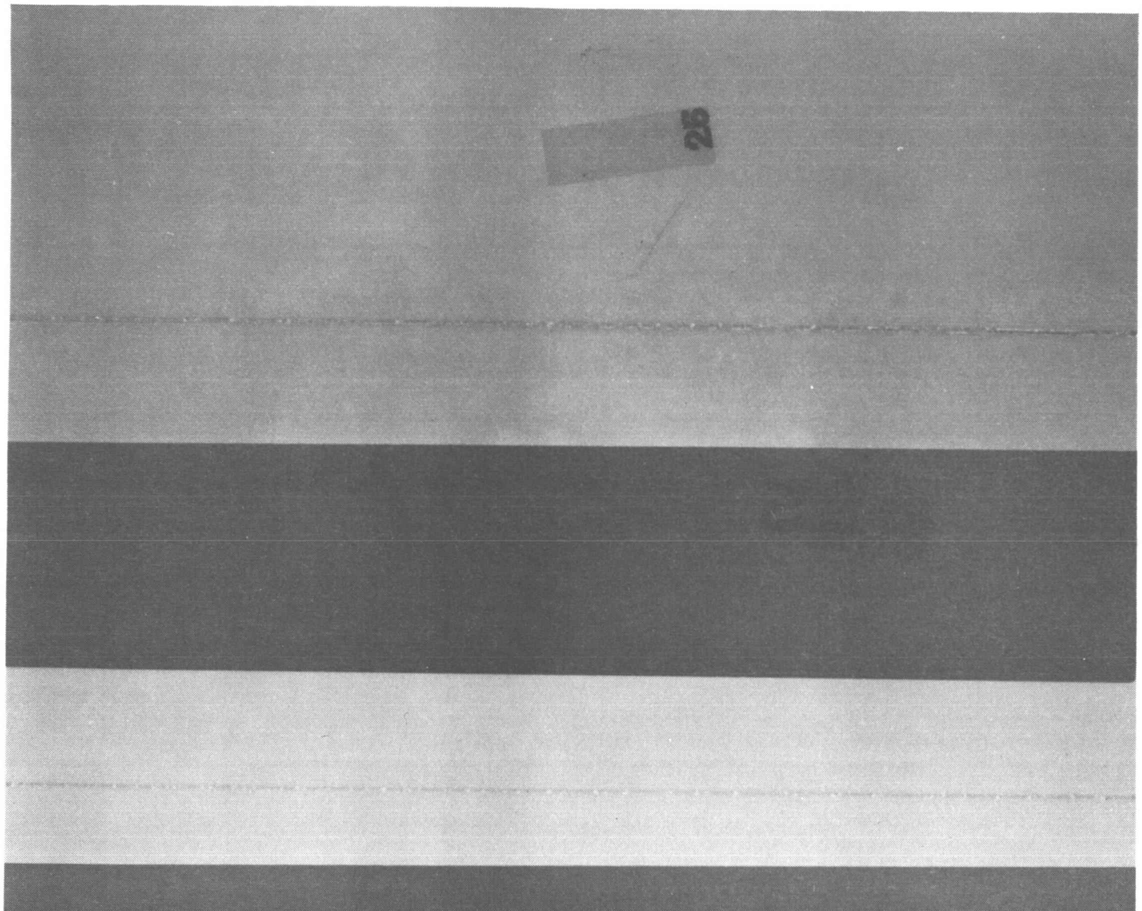
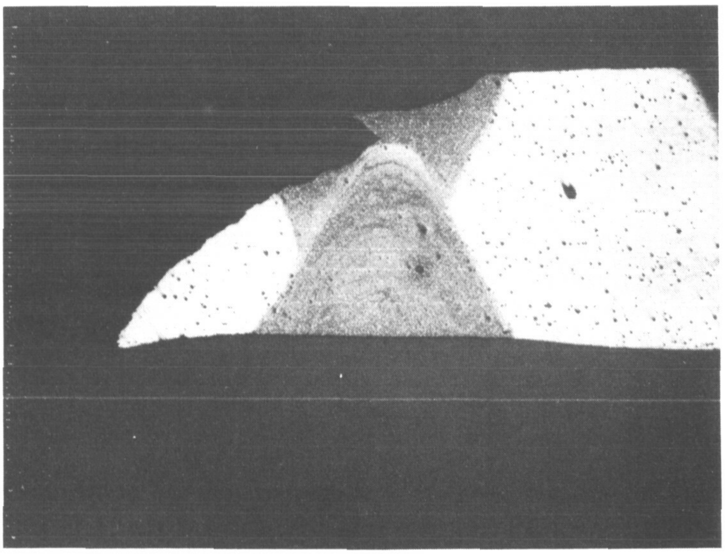


Figure 12. Radiographs of electron beam welded AZ31 magnesium test plates.

is a sort of chain reaction of cause and effect that defies ready remedial action. If the current surges are high enough, it is possible to "burn" holes in the sheets being welded.

Figure 12 is a contact print of the radiographs of the three magnesium test plates. Interpretation of these radiographs must be made with caution. Many of the indications that would normally be interpreted as porosity are actually images of the pits in the weld beads. This was determined by aligning the radiographs with the test plates and noting that the "porosity indications" nearly always correspond to the pits. In general, the porosity indications in the radiographs are not the proper size or shape for true pores.

Figure 13 is a photomicrograph of a typical cross-sectioned weld. Mechanical strength data at the various test temperatures is presented in Table 5.



Mag. 50X Etchant: Tartaric Acid

Figure 13. Photomicrograph of electron beam welded AZ31B magnesium sheet specimen (0.062 inch), which had been tensile tested at room temperature (30.6 ksi and 1.5 percent el.), showing the fracture in relation to the weld-base metal.

Test Temperature, °F		0.060 inch		0.070 inch		0.080 inch	
		Ftu	Percent Elong.	Ftu	Percent Elong.	Ftu	Percent Elong.
+250		24.9	12	26.8	24	23.8	10
		21.8	14	25.3	59	25.5	12
		27.3	22	23.3	57	27.3	9
	$\bar{X}$	24.7	16	25.1	47	25.5	10
	σ	3.9	5.3	1.8	20	1.7	2
+ 70		32.3	1.5	37.5	3.0	31.0	1.5
		30.6	1.5	37.6	2.0	29.6	1.5
		33.2	2.0	34.6	2.5	32.3	1.5
	$\bar{X}$	32.0	1.7	36.6	2.5	31.0	1.5
	σ	1.3	0.3	1.7	0.5	1.0	0
-100		40.0	1.0	44.1	2.5	36.4	1.0
		40.9	---	42.4	2.0	35.1	1.5
		38.0	---	41.9	2.0	34.8	1.5
	$\bar{X}$	39.6	1.0	42.8	2.2	35.4	1.3
	σ	1.5	0	1.2	0.3	0.8	0.3
-320		46.8	1.0	47.2	0.5	46.4	1.0
		47.5	0.5	53.3	1.5	46.3	1.0
		52.1	1.0	50.5	2.0	44.2	0.5
	$\bar{X}$	48.8	1.0	50.3	1.3	45.6	1.0
	σ	2.9	0.5	3.1	0.8	1.2	0.5

Table 5. AZ31B magnesium.

ALUMINUM

The two thinner gages, 0.012 inch and 0.020 inch thick, were very severely distorted by welding. Great difficulty was encountered in obtaining a satisfactory weld with the 0.012 inch gage stock. The sheet tended to warp very severely under the electron beam. In fact, the beam appeared to form a small concave cup in the stock at the point of impingement. If the distortion was not restrained, the faying edges would tend to warp away from one another, dropping the molten pool and leaving a hole burned in the stock. This problem was resolved by clamping the stock very close to the joint line with rigid tooling bars. The gap between the two hold-down bars was approximately 0.100 inch for generally successful welding. Figure 14 reveals a good weld bead for a portion of the test plate. There was no problem with burning when the 0.020 inch gage was welded with closely coupled tooling. The 0.032 inch gage was welded with a 1/2 inch gap between the tooling bars and no burning was encountered. However, a cracking problem was noted with the heaviest gage when the stock was not rigidly clamped.

Figure 15 is a contact print of the radiographs of the three weld beads. It should be noted that no porosity was produced in any of the welds. The cracks and burn-throughs at the unrestrained ends of the plates are readily apparent, just as they were visually. The weld bead was smooth and quite uniform on both sides in all instances.

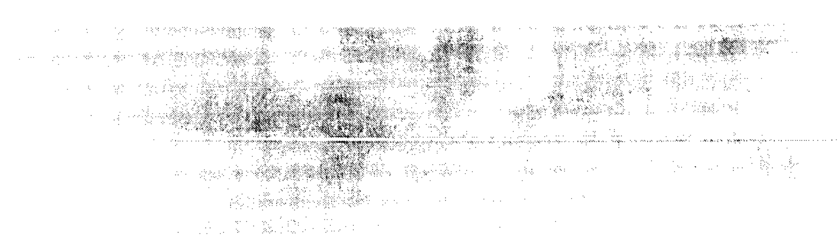


Figure 14. Electron beam welded aluminum plate revealing successful weld bead.

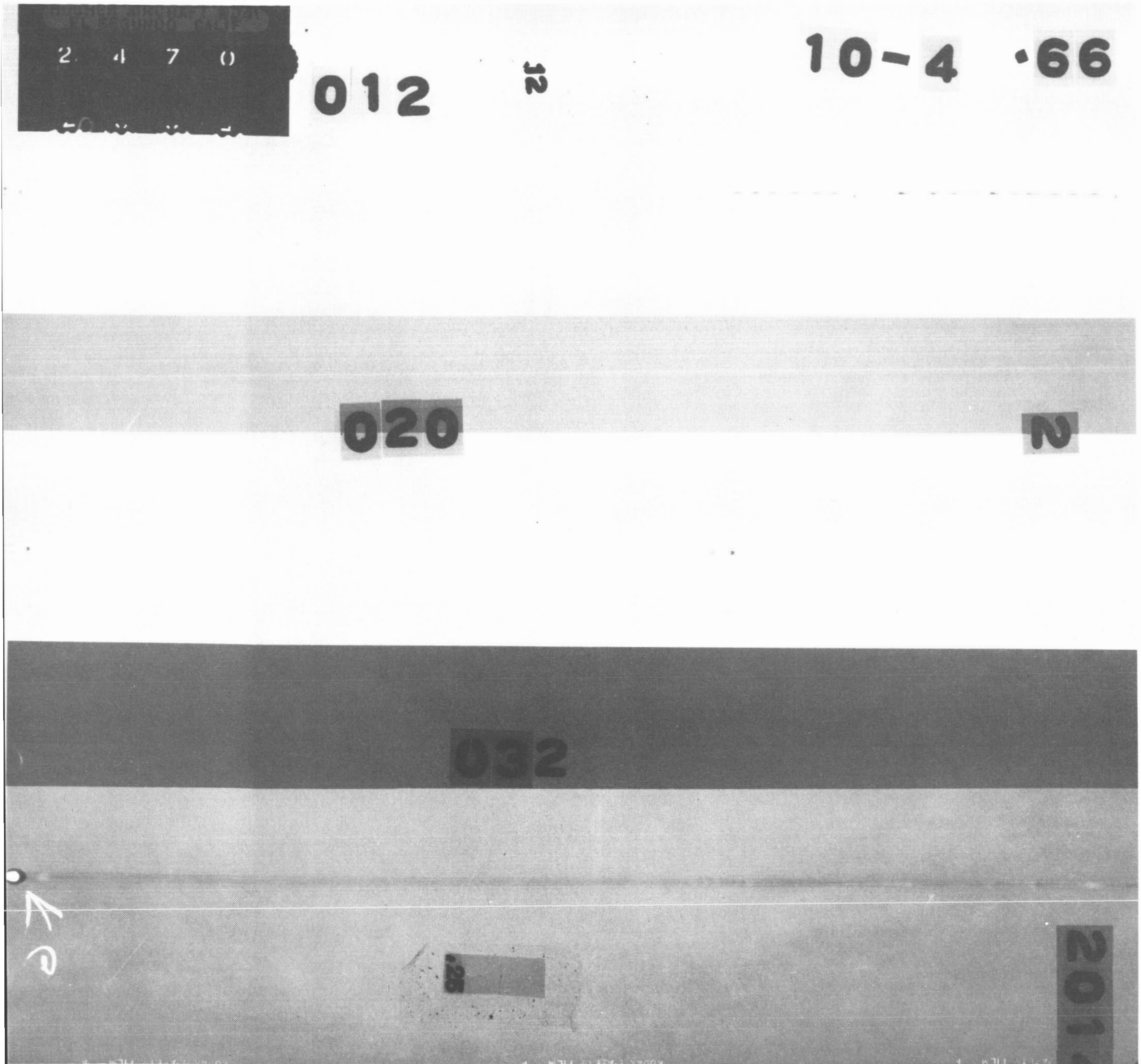
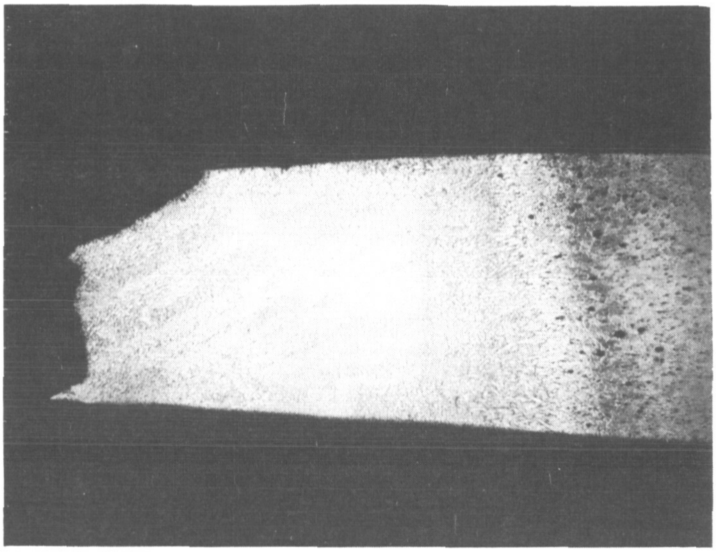


Figure 15. Three radiographs from electron beam welded 2014 aluminum test plates.

Figure 16 is a photomicrograph of a typical cross-sectioned weld. Mechanical strength data at the various test temperatures is presented in Table 6.



Mag. 100X　　　　Etchant: Kellers Reagent

Figure 16. Cross-section view of electron beam welded 2014 aluminum alloy sheet specimen (0.032 inch), which had been tensile tested at -320°F (60.7 ksi and 1.0 percent el.). Note that the fracture is through the base metal.

Test Temperature, °F	0.010 inch		0.020 inch		0.030 inch	
	Ftu	Percent Elong.	Ftu	Percent Elong.	Ftu	Percent Elong.
+250	30.0	0.5	42.7	1.5	43.0	1.5
	22.1	---	42.8	1.5	41.8	1.5
	33.8	1.0	42.0	1.5	41.8	1.5
$\overline{X}$	28.6	1.0	42.5	1.5	42.2	1.5
σ	6.1		0.4		0.7	
+ 70	37.0	1.0	45.4	1.0	46.1	1.5
	23.8	1.0	47.8	1.0	43.9	1.0
	31.2	1.0	41.0	1.0	45.8	1.5
$\overline{X}$	30.7	1.0	44.7	1.0	45.3	1.3
σ	6.6		3.4		1.2	
-100	32.9	0.5	47.8	1.0	46.9	1.0
	30.3	0.5	46.5	---	48.5	1.0
	36.4	1.0	45.5	---	49.1	1.0
$\overline{X}$	33.2	0.7	46.6	1.0	48.2	1.0
σ	3.1		1.2		1.1	
-320	35.0		63.8		57.3	1.0
	---		67.6		49.7	1.0
	48.5		63.6		60.7	1.0
$\overline{X}$	41.8		65.0		55.9	1.0
σ	9.5		2.3		5.6	

Table 6. 2014 Aluminum.

INCONEL 718/6Al-4V-TITANIUM

These welds were completely unsuccessful. In retrospect, this is highly logical and should have been predictable from the beginning. Differences in the thermal, physical and metallurgical characteristics of these two materials are great enough to make this combination unweldable from a practical point of view.

The heavy sectioned test plate cracked into two pieces along the weld bead as soon as the clamps on the welding fixture were released. This is shown in Figure 17, a photograph of this test plate.

The medium thickness plate was badly bowed as it was removed from the welding jig. The cracking of this plate could be heard as it was being visually examined after welding. The first half of the weld seam contained very few cracks but the last half had hair line cracks running transversely across the weld bead at approximately 1/4 inch intervals. The radiograph of this weld is shown in Figure 18. An attempt was made to process this test plate very carefully in order to obtain some strength data on this combination. Unfortunately, when the cut-off wheel touched the crown of the weld in the initial machining operation in preparing the test specimens, the plate shattered into two pieces along the weld bead. Incidentally, the plate was clamped in compression on a conformal rubber pad and the cut was being initiated at the weld bead (as a plunge cut) in an attempt to minimize machining damage.

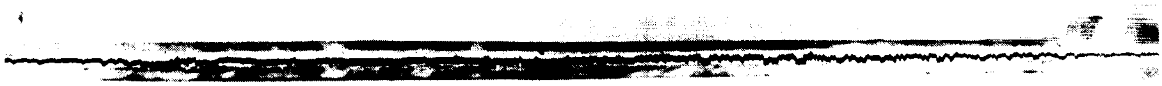


Figure 17. Fractured inconel 718/6Al-4V-titanium electron beam welded plates. (R112648)

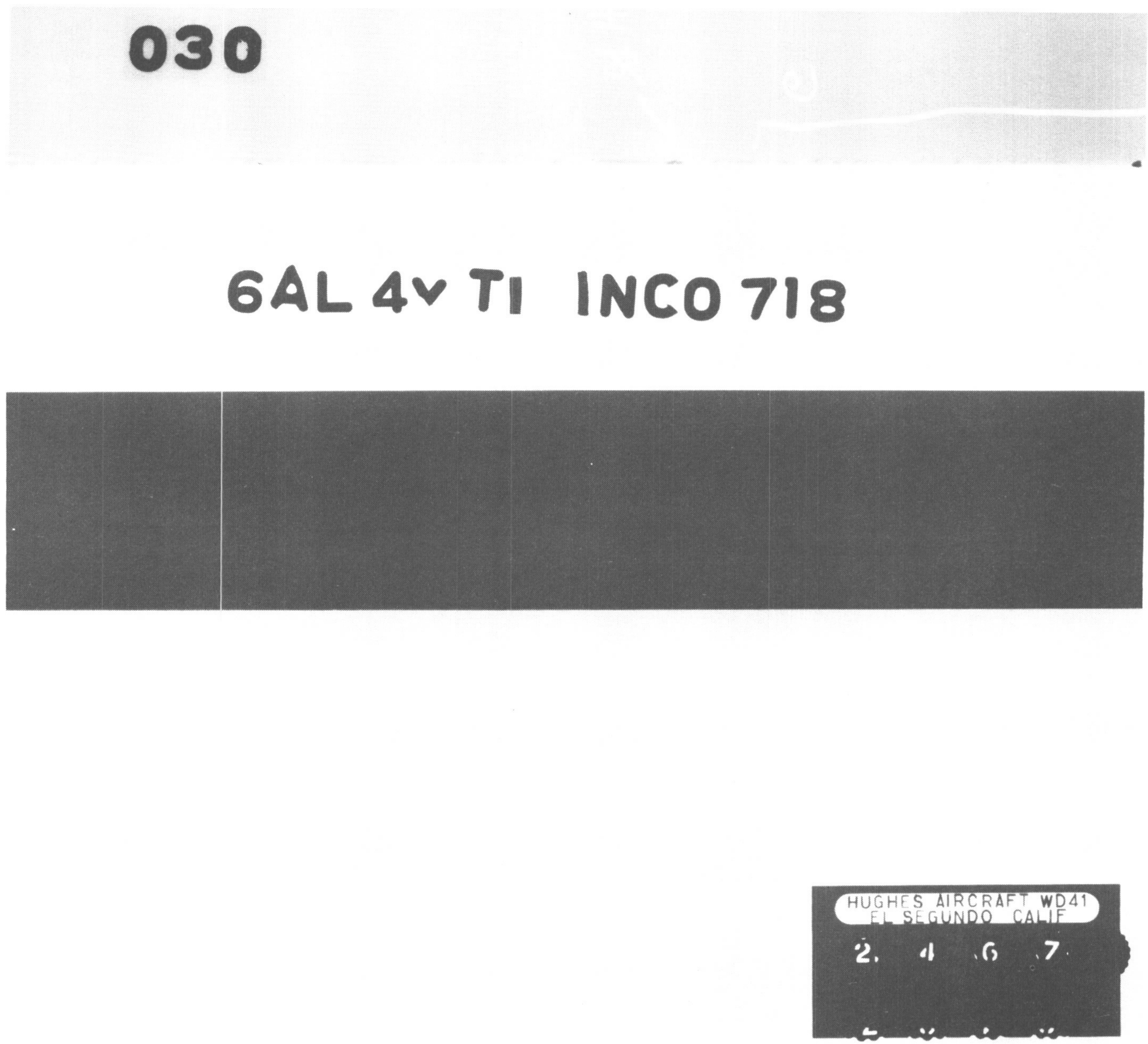
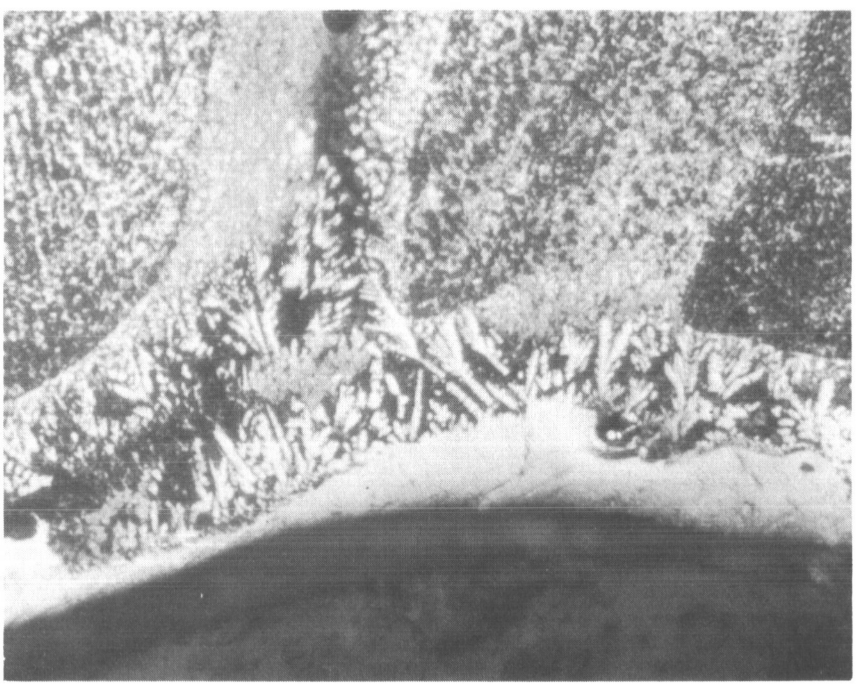


Figure 18. Radiograph taken of fractured electron beam welded Inconel 718-6A1-4V-titanium test plate.

The light gage weld plate was crack free but severely bowed after welding. It was broken during the radiographic inspection.

These results indicate that the weld joint contains a high proportion of brittle intermetallic compounds which cannot support the strain induced by the plastic deformation (bowing) caused by the difference in thermal expansion and heat-sinking characteristics of the two metals. Figure 19 is a photomicrograph of one of the weld joints which supports this contention.



Mag. 500X Etchant: Marbles

Figure 19. Cross-section of fractured Inconel 718 portion of embrittled Inconel 718/6Al-4V-titanium weldment. Note the presence of titanium-Inconel 718 intermetallic compounds.

6Al-4V-TITANIUM

These plates were welded very readily with no particular problems. The welds were smooth and uniform on both sides of the thinnest section. The weld crown was smooth and uniform on both of the thicker plates and the under bead was quite regular and as small as could be expected with reasonable assurance of penetration.

Figure 20 is a photograph of a typical weld bead while Figure 21 is a contact print of the radiographs of the weld beads. It should be noted that the heavier gages were free of porosity and only minimal porosity was found in the lightest gage. All welds were free of cracks, under cut and other deleterious defects.

Figure 22 is a photomicrograph of a typical cross-sectioned weld. Mechanical strength data at the various test temperatures is presented in Table 7.

INCONEL 718

No problems were encountered in welding these test plates. The weld beads were smooth and uniform with a minimum of undercutting and a small, well-controlled underbead. Figure 23 shows the typical bead configuration.

Figure 24 is a contact print of the radiographs of the weld beads. The two thicker plates were defect free but the thinnest plate contained one large pore and a number of smaller ones. The large pore may have been related to a weld interruption caused by arcing. The welder arced-out on this plate but was restarted and ran the seam to the satisfaction

Figure 20. Typical electron beam welded 6Al-4V-titanium test plates. (R112649)

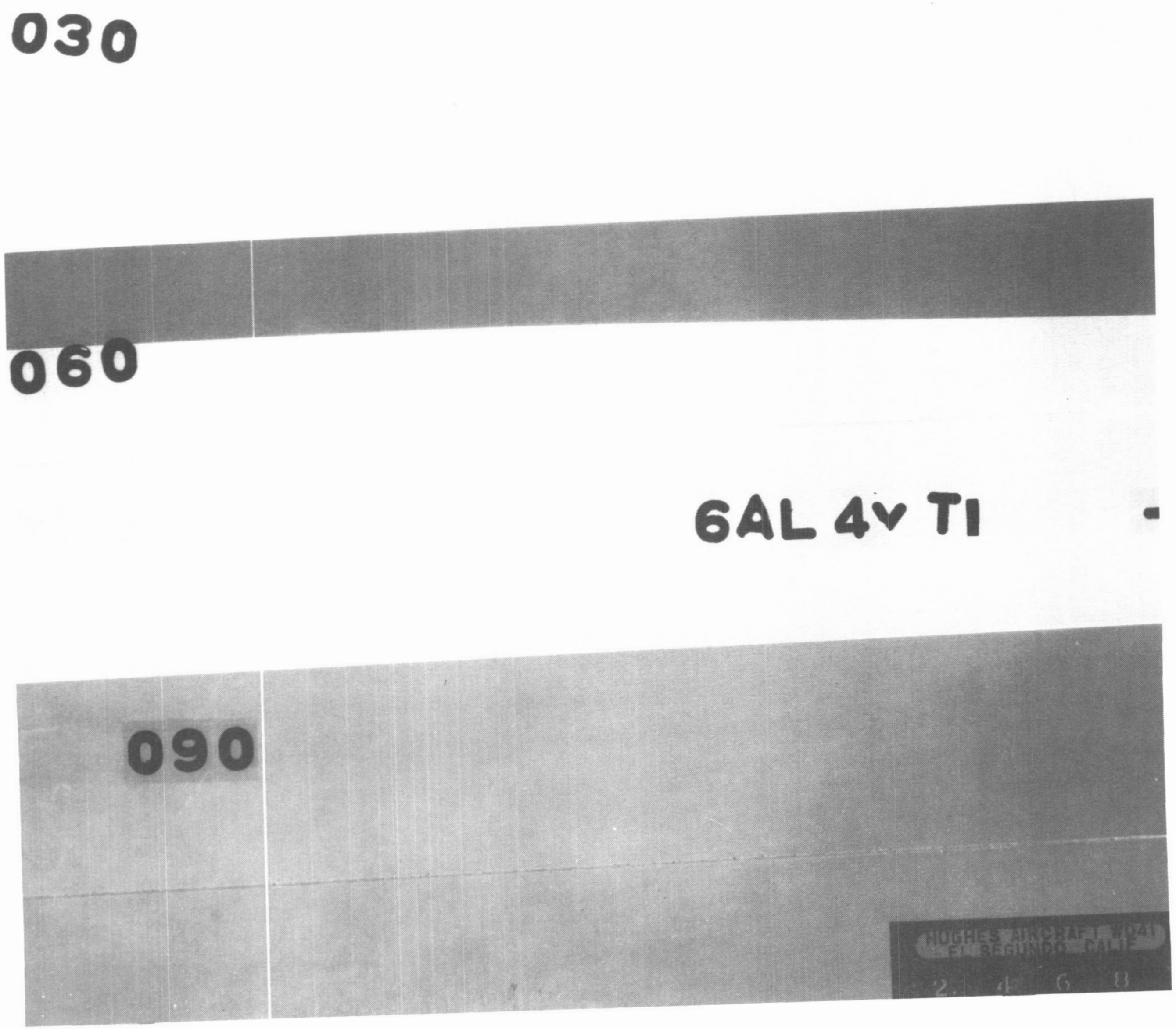
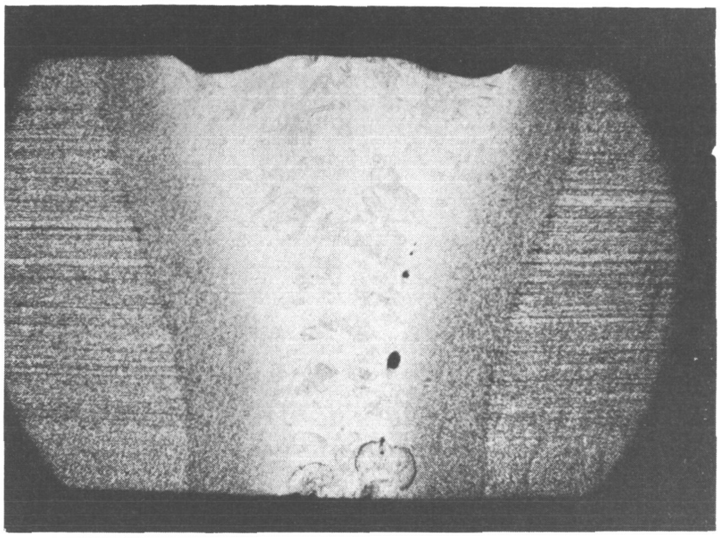


Figure 21. Radiographs of electron beam weldments of 6A1-4V-titanium test plates.



Mag. 50X Etchant: HNO_3-HF

Figure 22. Cross-section view of electron beam welded 6Al-4V-titanium alloy sheet specimen (0.090 inch) which had been tensile tested at room temperature (142.7 ksi and 10 percent el.). The fracture occurred within the base metal.

of the operator's visual inspection after welding. At any rate, there were no holes through the stock and no significant surface discontinuities.

Figure 25 is a photomicrograph of a typical cross-sectioned weld.

Mechanical strength data at the various test temperatures is presented in Table 8.

Test Temperature, °F		0.03 inch		0.07 inch		0.1 inch	
		Ftu	Percent Elong.	Ftu	Percent Elong.	Ftu	Percent Elong.
+250		113.6	7.0	111.0	0.5	116.8	13.0
		115.5	6.0	115.9	1.5	114.8	12.0
		115.5	7.0	118.6	2.5	115.9	6.0
	$\bar{X}$	114.9	6.7	115.2	1.5	115.8	10.0
	σ	1.1	0.6	3.5	1.0	1.0	3.8
+ 70		135.6	4.0	140.6	---	139.8	11.5
		148.1	6.0	138.5	---	142.7	10.0
		140.8	7.0	135.5	---	149.4	3.5
	$\bar{X}$	141.5	5.7	138.2	---	144.0	8.3
	σ	6.3	1.5	2.6	---	4.9	4.3
-100		159.9	6.0	164.5	1.0	158.2	10.0
		173.7	4.0	163.9	1.0	165.2	----
		156.4	7.0	161.9	---	162.0	5.0
	$\bar{X}$	163.3	5.7	163.4	1.0	161.8	7.5
	σ	9.1	1.5	1.4	0	3.5	2.5
-320		198.6	7.0	----	---	196.5	1.0
		198.6	6.0	261.5	1.0	269.6	4.0
		204.5	8.0	223.4	1.0	278.1	8.0
	$\bar{X}$	200.6	7.0	242.5	1.0	248.1	4.0
	σ	3.4	1.0	26.9	0.	44.9	4.0

Table 7. 6Al-4V-Titanium.

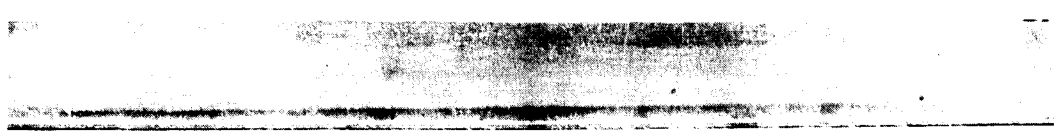


Figure 23. Typical electron beam welded Inconel 718 test plate. (R112651)

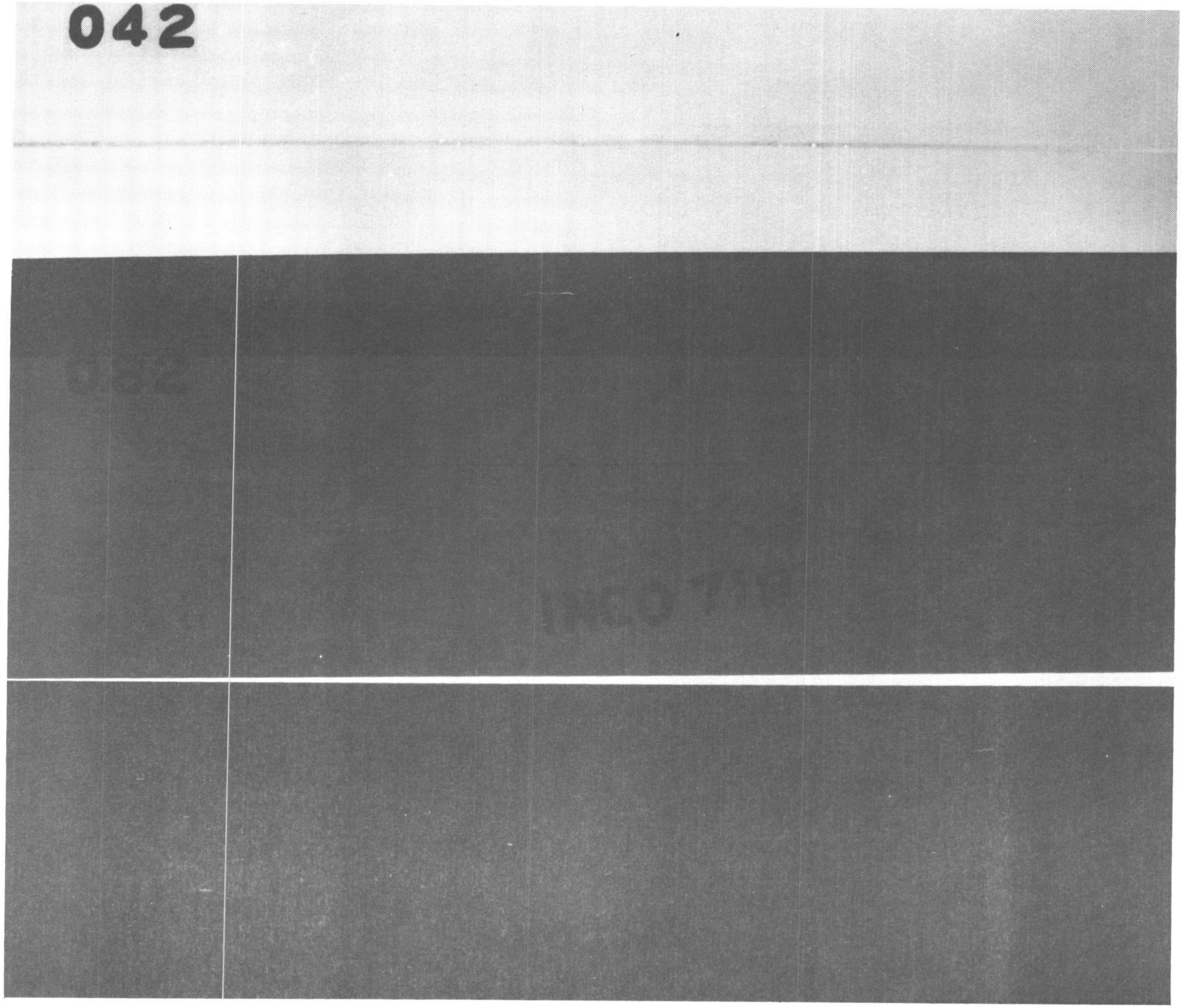
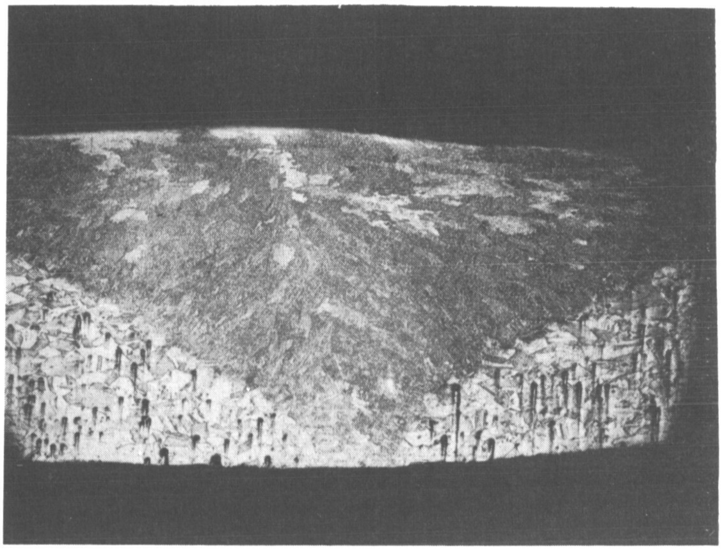


Figure 24. Radiographs of electron beam welded Inconel 718 test plates.



Mag. 50X Etchant: Marbles

Figure 25. Photomicrograph of electron beam welded Inconel 718 sheet specimen (0.078 inch) which had been tensile tested at 250°F (103.1 ksi and 46 percent el.). The fracture has occurred within the base metal.

Test Temperature, °F		0.040 inch		0.080 inch		0.125 inch	
		Ftu	Percent Elong.	Ftu	Percent Elong.	Ftu	Percent Elong.
+250		110.7	20.0	102.5	53.0	97.5	39.0
		112.9	19.0	103.1	46.0	98.8	38.0
		106.0	18.0	103.2	53.0	99.3	41.0
	$\overline{X}$	109.9	19.0	102.9	51.0	98.5	39.0
	σ	3.5	1.0	0.3	4.0	0.9	1.6
+ 70		96.7	32.0	100.0	52.0	109.8	38.0
		113.3	22.0	114.0	51.0	112.4	36.0
		116.4	19.0	----	----	107.2	52.0
	$\overline{X}$	108.8	24.0	107.0	51.0	109.8	42.0
	σ	10.6	7.0	7.0	1.0	2.6	8.8
-100		133.5	22.0	126.8	54.0	94.6	46.0
		135.5	23.0	126.1	52.0	109.9	26.0
		134.0	---	128.5	56.0	128.7	51.0
	$\overline{X}$	134.3	23.0	127.1	54.0	111.1	41.0
	σ	1.0	1.0	1.2	2.0	17.1	13.0
-320		144.7	19.0	134.5	29.0	126.0	21.0
		158.0	20.0	132.4	26.0	132.3	30.0
		156.6	20.0	130.2	32.0	130.5	29.0
	$\overline{X}$	153.1	20.0	132.4	29.0	129.6	27.0
	σ	7.3	0.6	2.1	3.0	3.2	4.9

Table 8. Inconel 718.

RESISTANCE WELDING/BRAZING/SOLDERING

The resistance seam welding apparatus was adapted for remotely controlled operation inside a vacuum bell-jar as shown in Figure 26. Inside the base ring, in the photograph, at the left side are the hermetically sealed direct current drive motor and reduction gear for powering the electrode wheels. Between the drive motor and the weld head is a solenoid which was used to apply the clamping force to the weld head through the cable and pulley assembly running through the mounting board at the lower right side of the picture. The plastic specimen carrier was designed to ride along the rails between the electrodes. It was found that a tension spring had to be attached to the specimen carrier to obtain consistent travel of the specimen during welding. Until this modification was made, "spotty" and inconsistent joints were obtained. The spring exerted a modest tension, approximately 2 pounds on the specimen.

The machine was operated at a clamping force of approximately 18-20 pounds, a welding voltage of 1.99 volts with a welding current of approximately 800 amperes for all materials and gage thicknesses. Only the welding speed was varied, depending upon the materials and thicknesses to be welded, brazed or soldered. This required some changes in pulse length to assure that energy was applied across the full width of the specimen only.

Tests were run at hard vacuum, using diffusion pumping to obtain levels of 10^{-6} torr; at "softer" vacuums of the order of magnitude of the low micron pressure range obtained with mechanical pumping only; and at ambient pressures. No difference in joint strength or system performance was noted in any of these tests. This is significant in assessing the problem of welding in a cabin atmosphere.

The oxidizing potential of a gaseous environment is a function of the partial pressure of oxygen present in the atmosphere. If a 10 psia mixture of 50 percent oxygen and a 50 percent chemically inert diluent gas such as nitrogen is employed, the activity of the oxygen present

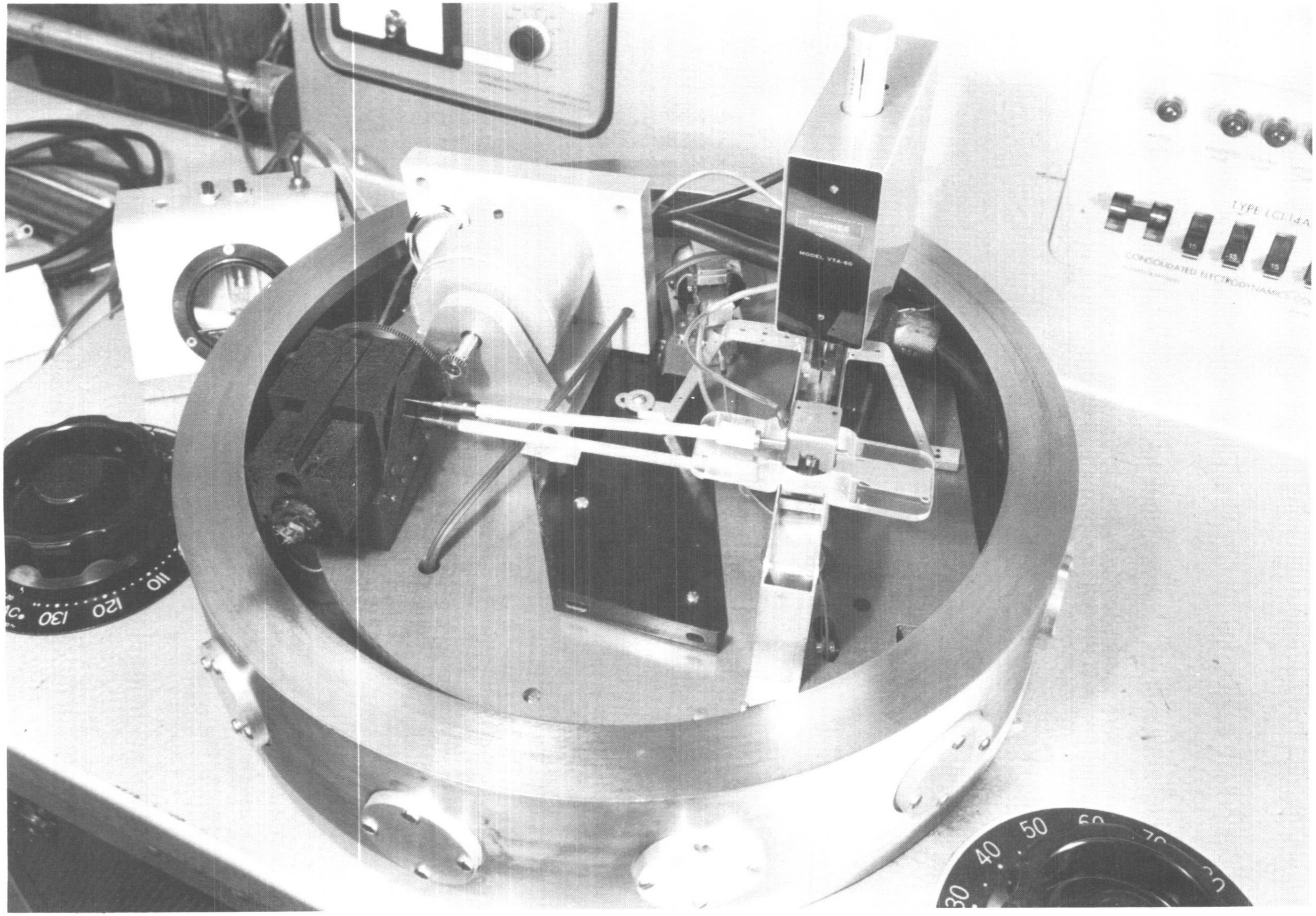


Figure 26. Resistance seam welding equipment set up for welding/soldering/brazing in a vacuum environment. (R113288)

will be approximately 0.33. Thus:

$$\frac{10 \text{ psia}}{15 \text{ psia (1 atmosphere)}} \times 0.5 \text{ (concentration of } 0_2) = 0.33.$$

This is approximately the same order of magnitude as the chemical activity of oxygen in a normal environment (0.2). Thus:

$$1 \text{ atmosphere} \times 0.2 \text{ (concentration of } 0_2) = 0.2.$$

One other significant factor to be noted from this study is that the power demand is below the 1800 watt bogey for the system (1.99 volts x 800 amperes = 1592 watts).

Problems were encountered in welding the heaviest gage of aluminum and in brazing the thickest section of titanium but there are solutions available for these problems. Each of the materials combinations are discussed separately.

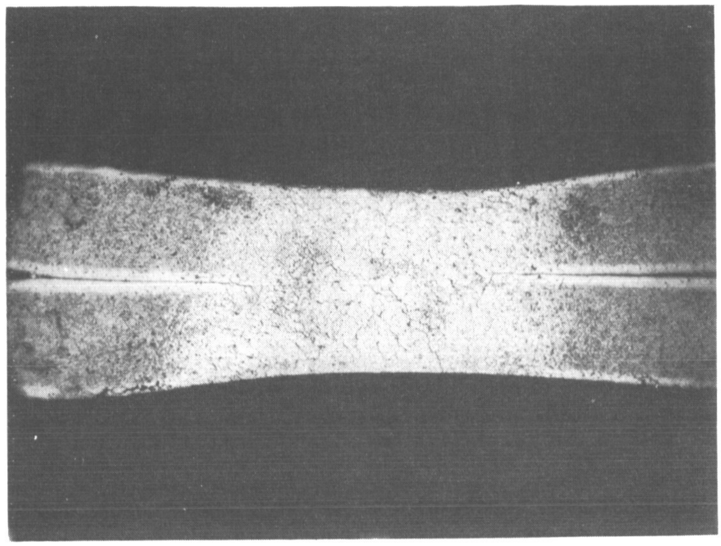
ALUMINUM

The 0.012 inch and 0.020 inch thick aluminum samples were resistance seam welded using the stainless steel plates between the electrodes and the samples as described in earlier monthly reports. The 0.012 inch thick specimens were welded at a speed of 11.4 inches per minute resulting in a heat input of 8.4 kilojoules/inch. The 0.020 inch thick specimens were welded at 9.0 inches/minute which resulted in a specific energy input of 10.7 kilojoules/inch.

The 0.032 inch stock was too heavy to be welded or brazed satisfactorily. It was, therefore, abandoned. However, it should be possible to prepare a tinned surface for soldering by a combination of a zincate "flash" and copper plating with a hot dip solder tin on top.

Figure 27 is a photomicrograph of a typical cross-sectioned resistance seam weld.

Results of the mechanical test program are summarized in Table 9.



Mag. 50X Etchant: Kellers Reagent

Figure 27. Photomicrograph showing cross-sectional view through 2014 aluminum alloy lap joint.

Test Temperature, °F		0.012 inch F_{su} (ksi)	0.020 inch F_{su} (ksi)
+250		2.5	3.5
		1.5	2.5
		2.8	3.9
	$\overline{X}$	2.3	3.3
	σ	0.6	0.6
+ 70		3.6	3.2
		2.8	4.0
		3.3	3.8
	$\overline{X}$	3.2	3.7
	σ	0.3	0.3
-100		1.8	4.4
		1.4	3.7
		1.4	4.4
	$\overline{X}$	1.5	4.1
	σ	0.1	0.3
-320		3.7	2.9
		2.8	3.4
		3.6	2.8
	$\overline{X}$	3.3	3.0
	σ	0.4	0.3

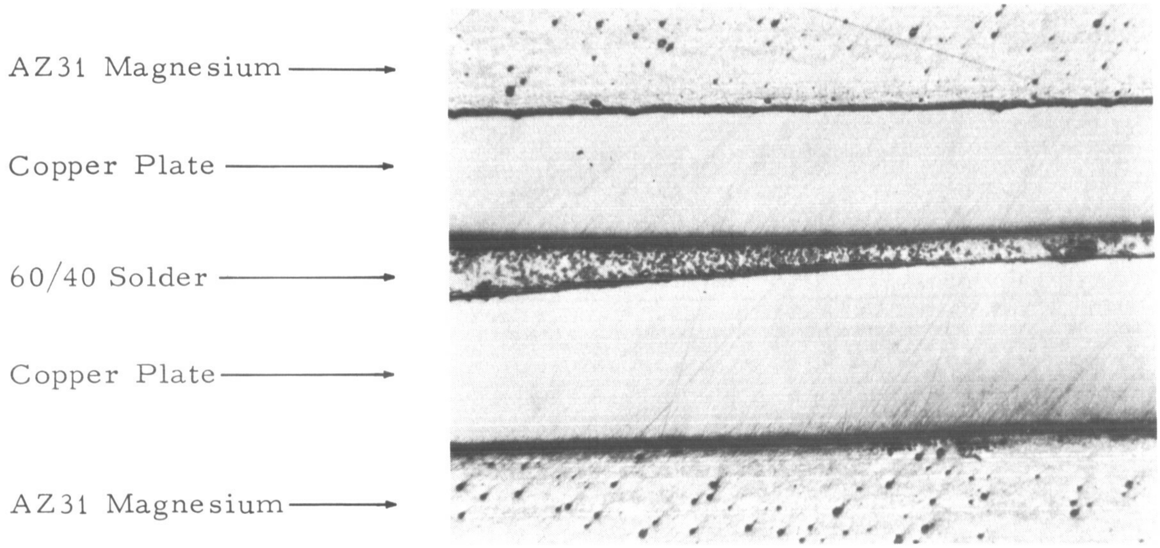
Table 9. 2014 Aluminum.

MAGNESIUM

The magnesium specimens were copper plated and hot tinned with 60 percent weight Sn/40 percent weight Pb solder. They were then resistance soldered at 5.4 inches/minute. No problems were encountered in these tests.

Figure 28 is a photomicrograph of a typical cross-section of one of these resistance soldered specimens.

Results of the mechanical tests at the various temperatures are presented in Table 10.



Mag. 80X Etchant: Tartaric Acid

Figure 28. Cross-section of resistance soldered AZ31B magnesium lap joint. A 60-40 solder was wetted onto the copper plated specimens prior to resistance soldering.

Test Temperature, $^{\circ}F$		0.060 inch F_{su} (ksi)	0.070 inch F_{su} (ksi)	0.080 inch F_{su} (ksi)
+250		1.7	1.3	1.3
		1.9	1.2	1.6
		1.8	1.6	1.2
	$\overline{X}$	1.8	1.4	1.4
	σ	0.1	0.2	0.2
+ 70		2.2	1.9	2.1
		3.6	1.8	3.1
		2.5	1.6	1.8
	$\overline{X}$	2.8	1.8	2.3
	σ	0.6	0.1	0.6
-100		3.8	2.9	4.5
		4.2	3.1	3.4
		3.6	3.2	2.5
	$\overline{X}$	3.9	3.1	3.5
	σ	0.4	0.1	0.8
-320		2.9	3.0	4.2
		4.2	3.6	4.9
		3.8	2.9	4.0
	$\overline{X}$	3.6	3.2	4.4
	σ	0.5	0.3	0.4

Table 10. AZ31 magnesium.

INCONEL 718

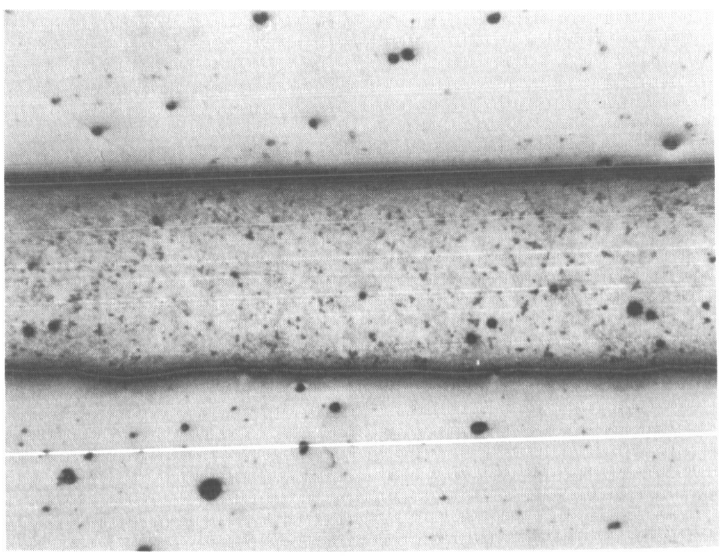
These samples were cleaned, fluxed and hot tinned with 60/40 solder. They were then resistance soldered at the following speeds:

Thickness, inches	Speed, ipm
0.040	5.4
0.080	5.4
0.125	3.2

No problems were encountered in soldering these test specimens.

Figure 29 is a photomicrograph of a typical cross-section of one of these resistance soldered test specimens.

Results of the mechanical tests at the various test temperatures are presented in Table 11.



Mag. 80X Unetched

Figure 29. Cross-section of resistance soldered lap joint of Inconel 718.

Test Temperature, ^{o}F		0.043 inch F_{su} (ksi)	0.078 inch F_{su} (ksi)	0.125 inch F_{su} (ksi)
+250		0.6	1.2	2.0
		1.0	1.6	0.4
		1.2	1.3	1.5
	$\overline{X}$	0.9	1.4	1.3
	σ	0.3	0.2	0.7
+ 70		1.4	1.3	1.2
		2.7	1.8	1.1
		1.6	2.0	2.3
	$\overline{X}$	1.9	1.7	1.5
	σ	0.6	0.3	0.6
-100		2.3	4.0	1.5
		4.5	3.3	1.4
		2.0	3.5	2.6
	$\overline{X}$	2.9	3.6	1.9
	σ	1.1	0.3	0.6
-320		3.6	4.4	1.8
		3.8	3.3	3.7
		3.7	4.1	3.0
	$\overline{X}$	3.7	3.9	2.8
	σ	0.1	0.6	0.8

Table 11. Inconel 718.

6Al-4V-TITANIUM

The 0.030 and 0.060 inch gages were joined by resistance brazing using a 13 percent silicon - balance aluminum filler alloy. These brazing operations were performed at 10.2 and 5.4 inches/minute for the 0.030 inch and 0.060 inch gages, respectively. The 0.090 inch gage titanium could not be resistance brazed due to its greater thickness which prevented adequate heating at the faying surface to promote brazing. Consequently, the faying surfaces were electroplated with 0.001 inch of copper, preceded by a "flash" of nickel, coated with 60 percent weight Sn - 40 percent weight Pb solder and finally resistance soldered at 3.2 inches/minute.

Figure 30 shows the cross-section of a typical resistance brazed joint.

The results of mechanical tests of these specimens at the various test temperatures are presented in Table 12.

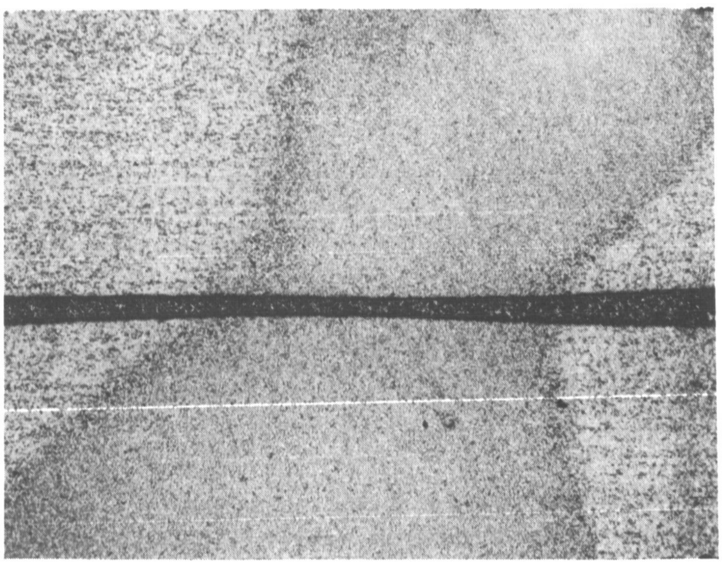


Figure 30. Photomicrograph of cross-section of 6Al-4V titanium joint with Al-Si filler alloy brazed to titanium.

Etchant: 3 percent HF, 6 percent HNO_3
Balance H_2O

Mag. 80X

Test Temperature, °F		0.036 inch F_{su} (ksi)	0.060 inch F_{su} (ksi)	0.090 inch F_{su} (ksi)
+250		13.9	10.4	1.8
		9.2	12.3	2.0
		10.2	9.1	1.9
	$\overline{X}$	11.1	10.6	1.9
	σ	2.0	1.3	0.1
+ 70		12.3	9.0	3.8
		8.7	9.5	3.2
		12.1	11.2	2.3
	$\overline{X}$	11.0	9.9	3.1
	σ	1.6	0.9	0.6
-100		14.0	9.0	4.3
		11.0	8.4	7.6
		13.3	5.0	5.0
	$\overline{X}$	12.8	7.5	5.6
	σ	1.2	1.5	1.4
-320		13.1	13.2	1.8
		13.7	11.3	2.0
		11.1	12.8	1.9
	$\overline{X}$	12.6	12.4	1.9
	σ	1.1	0.7	0.1

Table 12. 6Al-4V-titanium.

INCONEL 718/6Al-4V-TITANIUM

It was determined that these materials could not be directly resistance welded nor brazed with the aluminum silicon filler alloy. As an alternative, resistance soldering with the 60/40 alloy was employed. Although the Inconel 718 could readily be wetted with the solder alloy, the titanium had to be electroplated with copper followed by wetting the solder to this substrate. The resistance soldering speeds were approximately the same as those employed for joining the titanium specimens. Figure 31 is a photomicrograph of a typical resistance soldered specimen.

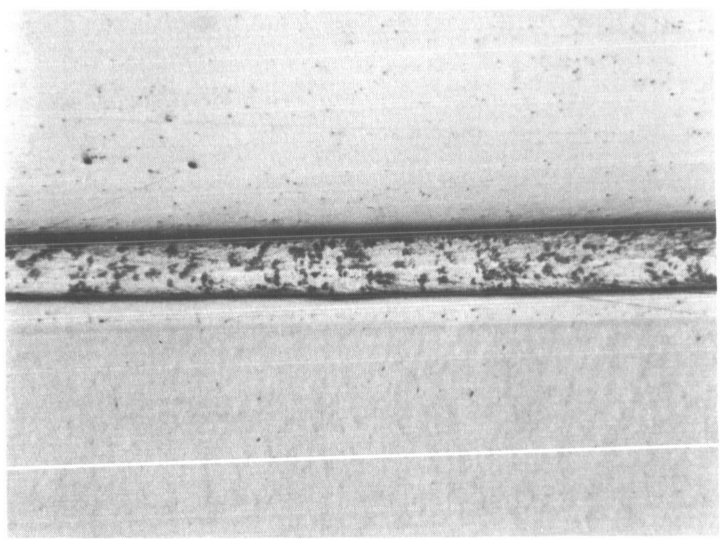
Presented in Table 13 are the results of the mechanical tests conducted on these specimens at the various temperatures.

Inconel 718

60/40 Solder

Copper Plate

6Al-4V-Titanium



Mag. 80X Unetched

Figure 31. Cross-section of a resistance soldered lap joint between Inconel 718 and copper plated 6Al-4V-titanium.

Test Temperature, ^{o}F		0.040 Inconel 718/ 0.030 6Al-4V-Titanium F_{su} (ksi)	0.078 Inconel 718/ 0.060 6Al-4V-Titanium F_{su} (ksi)	0.125 Inconel 718/ 0.090 6Al-4V-Titanium F_{su} (ksi)
+250		2.0	1.5	1.3
		2.0	1.9	1.2
		1.0	1.5	1.9
	$\overline{X}$	1.7	1.6	1.5
	σ	0.4	0.2	0.3
+ 70		4.6	4.2	2.6
		5.4	4.1	4.2
		3.3	3.3	3.6
	$\overline{X}$	4.4	3.9	3.5
	σ	0.9	0.4	0.7
-100		6.1	3.3	3.7
		5.5	4.9	4.5
		4.9	5.0	5.4
	$\overline{X}$	5.5	4.4	4.5
	σ	0.5	0.8	0.7
-320		3.2	3.6	4.0
		4.2	2.8	4.9
		4.6	3.6	4.2
	$\overline{X}$	4.0	3.3	4.4
	σ	0.6	0.4	0.4

Table 13. Inconel 718/6Al-4V-titanium.

LEAK TESTING AND THERMAL CYCLING

Small "pressure vessels" were machined of the various alloys to be evaluated in this program. Cover plates of the gage thicknesses to be tested were joined to the vessel bodies by the processes developed in the feasibility demonstration phase. Two different leak test vessel designs were used as shown in Figures 32 and 33. The straight-walled cup was used for electron beam welding tests where the cover plate was welded to the top surface of the cup wall with a single penetration pass. The flanged vessels were used for resistance welding/brazing/soldering tests. The flanges were machined to the same thickness as the cover plates and the joint was consummated by pinching the flange and cover plate between the electrode wheels.

A detailed description of the welding practices is presented in the following sections of this report.

ELECTRON BEAM WELDING

The vessels were mounted in a pot-chuck type of fixture that restricted movement of the part during welding. The upper surface of the vessel wall protruded approximately 0.020 inches above the top surface of the fixture so that the cover plate could be clamped onto the vessel with a shroud-type of hold-down tool. Slots were milled in the backside of the shroud so that feeler gages could be inserted at several places to ensure good contact between the cover plate and the vessel wall. The parts were welded with a single practice pass using both up and down slope control to prevent the occurrence of weld defects at the start and stop points.

The welding schedules that were used for the preparation of vessels for test purposes are presented in Table 14. These schedules differ somewhat from those used for welding the tensile test samples in the feasibility demonstration phase. The reason for this is that a greater depth of penetration is needed for welding the leak test vessels and there is a greater heat sink involved by virtue of the joint design.

No attempt was made to weld the Inconel 718/6Al-4V-Titanium combination because of the very poor results obtained from welding the

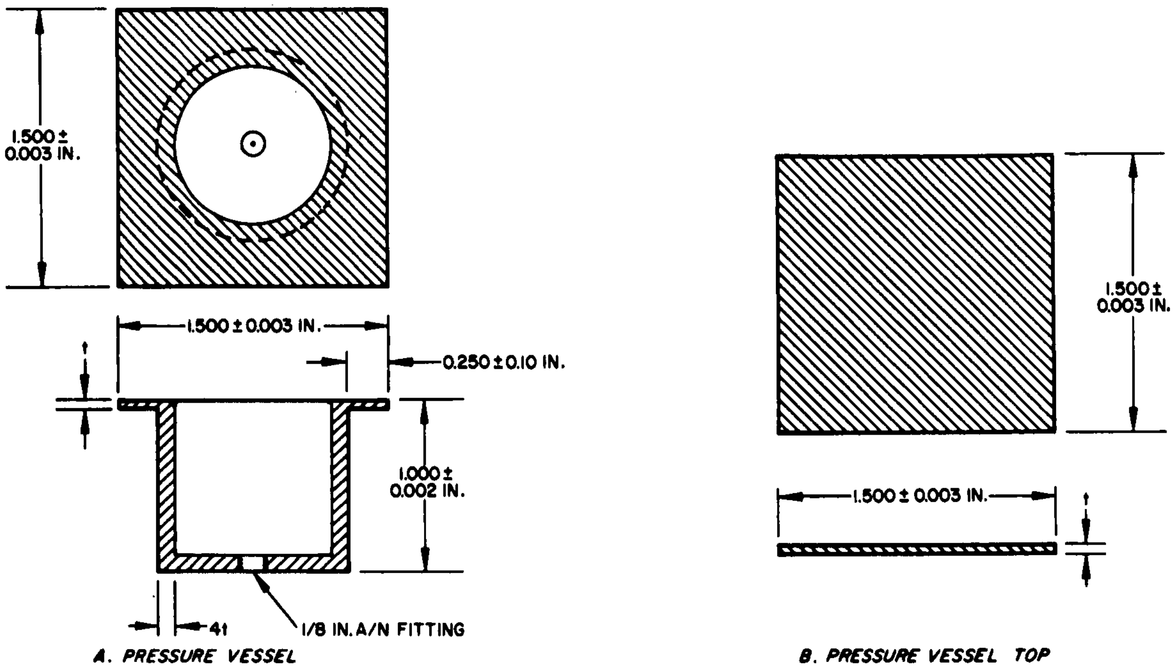


Figure 32. Rectangular vessel.

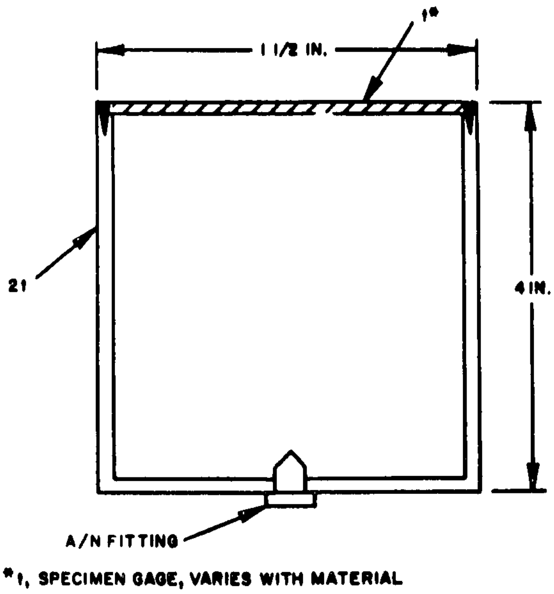


Figure 33. Cross-section of pressure vessel design suitable for welding.

Material	2014 Aluminum	2014 Aluminum
Gage thickness	0.020 inch	0.032 inch
Emitter/cathode distance	0.357 inch	0.357 inch
Cathode size	0.160 inch diameter	0.160 inch diameter
Cathode/anode spacer	0.200 inch	0.300 inch
Accelerating voltage	20.0 KV	30.0 KV
Beam current	23 ma	27 ma
Power	460 watts	810 watts
Welding speed	20 ipm	20 ipm
Specific energy	1380 j/inch	2430 j/inch
Focal length	2 inches	2 inches
Focus current	3.6 amperes	4.4 amperes

Material	Inconel 718	Inconel 718	Inconel 718
Gage thickness	0.043 inch	0.078 inch	0.125 inch
Emitter/cathode distance	0.347 inch	0.347 inch	0.347 inch
Cathode size	0.160 inch diameter	0.160 inch diameter	0.160 inch diameter
Cathode/anode spacer	0.300 inch	0.200 inch	0.100 inch
Accelerating voltage	20.0 KV	20.0 KV	20.0 KV
Beam current	32 ma	40 ma	52 ma
Power	640 watts	800 watts	1040 watts
Welding speed	20 ipm	15 ipm	20 ipm
Specific energy	1920 j/inch	3200 j/inch	3120 j/inch
Focal length	2 inches	2 inches	2 inches
Focus current	3.9 amperes	3.9 amperes	3.9 amperes

Material	6Al-4V-Titanium	6Al-4V-Titanium	6Al-4V-Titanium
Gage thickness	0.036 inch	0.072 inch	0.090 inch
Emitter/cathode distance	0.347 inch	0.347 inch	0.347 inch
Cathode size	0.160 inch diameter	0.160 inch diameter	0.160 inch diameter
Cathode/anode spacer	1.400 inch	0.300 inch	0.200 inch
Accelerating voltage	20.0 KV	20.0 KV	20.0 KV
Beam current	16 ma	32 ma	40 ma
Power	320 watts	640 watts	800 watts
Welding speed	15 ipm	20 ipm	20 ipm
Specific energy	1280 j/inch	1920 j/inch	2400 j/inch
Focal length	2 inches	2 inches	2 inches
Focus current	3.9 amperes	3.9 amperes	3.9 amperes

Table 14. Electron beam weld schedules used in preparing leak test vessels.

tensile specimens for the feasibility demonstration phase of the program.

Many different practices were tried in an attempt to obtain satisfactory welded joints with the lightest gage aluminum and all three gages of magnesium. None were successful. The light gage aluminum buckled in all cases regardless of tooling or welding procedures and resulted in a "cut" cover sheet rather than a welded one. The magnesium could not be electron beam welded by any practice used because of pitting resulting from excessive vaporization of the metal. It was not possible to obtain a power setting that would permit a full penetration weld without vaporization and arcing problems. Figure 34 is a photograph showing the surface pitting obtained with this material. Neither welding speed nor beam power density (variations in accelerating voltage, beam current and/or focus) were effective in correcting this problem.

All welded vessels were subjected to a "coarse", preliminary leak test with low pressure air in a tank of water. No air bubbles were observed in any of the titanium, Inconel or the heavier gage aluminum test vessels. These vessels were then subjected to a helium leak test on a CEC Model 24-120A Leak Detector. Some of the vessels exhibited a leak rate that was adjudged to be unacceptable and were excluded from further testing. Generally speaking, it would appear that the results indicated that an improper welding schedule was used on one gage thickness of titanium and one gage thickness of Inconel. It is probable that the beam power was slightly too low to obtain uniformly full penetration across the faying surfaces. The results obtained from the other gage thicknesses of the same material would indicate that there are no major problems related to the materials themselves which would impair successful joining if proper welding procedures are employed.

The vessels which passed the first leak test all exhibited leak rates of the order of magnitude of 10^{-10} of He/second. These vessels were then subjected to 100 cycles of thermal shock. Each cycle consisted of one full excursion from -250°F to +250°F and back down to -250°F. The specimens were loaded onto a rack which was designed for the cycling tests. The rack was placed in a deep dewar containing liquid nitrogen,

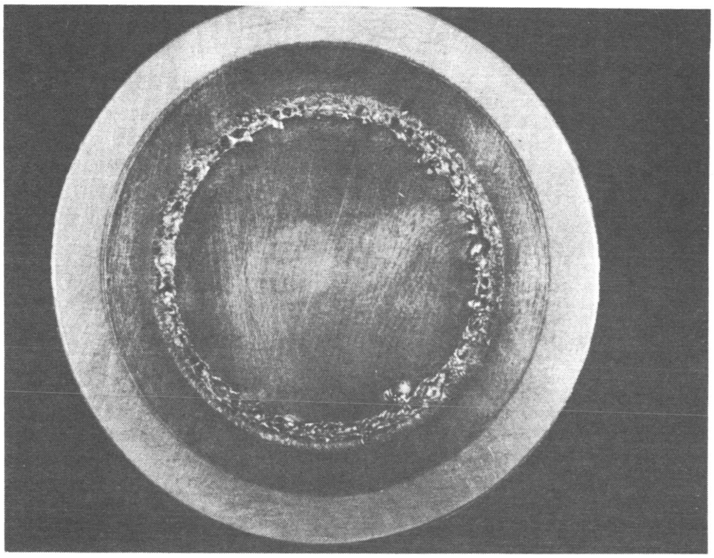


Figure 34. AZ-31B magnesium leak-test vessel showing surface pitting resulting from excessive metal vaporization.

which resulted in a vigorous boiling of the liquid nitrogen. Additional cryogenic fluid was added as the boiling progressed. When the temperature of a "bugged" specimen reached -250°F, as indicated by an attached thermocouple, the rack was withdrawn and transferred to an oven preheated to 500°F. Preliminary tests using several strategically placed thermocouples showed that excellent temperature uniformity existed from specimen to specimen. The "thermal head" was necessary to hold the total testing time to a reasonable period so that all 100 cycles could be accomplished without stopping the testing. When the thermocouple indicated a temperature of +250°F, the rack of samples was transferred back to the dewar.

At the conclusion of the thermal cycling, the specimens were again subjected to a helium leak check. There was no change in leak rate as may be observed from the data tabulated in Table 15. This is a highly logical result since an hermetically tight weld would be a sound metallurgical joint possessing strength beyond that required to withstand stresses imposed by a mere 500°F thermal excursion.

RESISTANCE WELDING/BRAZING/SOLDERING

Prior to attempting fabrication of the leak test vessels, it was realized that great difficulty would be involved in providing adequate fixturing to conduct the weld tests on a vacuum environment The fixturing would have to be such as to keep the vessel specimen covers in intimate contact with and properly aligned to the vessel body during the time a weld was being made. Also, a translating system would be required to feed the vessels into the electrode wheels properly. Additionally, it was realized that as many as 12 distinct weldments might be required around the perimeter of the vessel. Therefore the vacuum would have to be "broken" and "drawn" for re-positioning of the vessel for each weld conducted to provide proper over-lapping of the welds to achieve a hermetic seal. This would have been an exceedingly costly, laborious, and time consuming procedure.

To determine if any difference in weld quality existed between specimens joined in air and vacuum lap shear specimens were fabricated in both environments, tensile tested and metallographically examined. No

Spec. Ident.	Material	Cover-Sheet Thickness	Joining Process	Helium Leak Rate (cc/sec. @1 atm.) Before Cycling	After Cycling*
1A	2014-T6	0.018	Electron Beam	$>2.6 \times 10^{-5}$	Not Tested
2A		0.018		$<2 \times 10^{-10}$	$<2 \times 10^{-10}$
3A		0.032			
4A		0.018			
5A		0.032			
6A		0.032			
1C	Inconel 718	0.120		$>1.4 \times 10^{-3}$	Not Tested
2C		0.121		$\sim 7.2 \times 10^{-4}$	Not Tested
3C		0.120		$\sim 7.2 \times 10^{-4}$	Not Tested
4C		0.083		$<2 \times 10^{-10}$	$<2 \times 10^{-10}$
5C		0.042			
6C		0.083			
7C		0.083			
8C		0.042			
9C		0.043			
1T	6Al-4V-Ti	0.073		$<2 \times 10^{-10}$	$<2 \times 10^{-10}$
2T		0.096			
3T		0.097			
4T		0.072			
5T		0.095			
6T		0.073			
7T		0.036		4.2×10^{-7}	
8T		0.034		$>3.5 \times 10^{-4}$	Not Tested
9T		0.034		$\sim 7.2 \times 10^{-5}$	Not Tested

*-250F to +250F to -250F

Table 15

difference in the strength or metallurgical characteristics of the specimens fabricated in these environments was noted. Based on the results of these tests, it was decided to manually conduct the fabrication of all vessels, of all materials and gages, in air. A further noteworthy consideration that favors this approach is that it would be a test of the ability of a human being to manipulate structural components manually, employing the resistance welding equipment. Consequently, if the technician in the laboratory could manually produce successful weldments, it would be an indication that the astronaut in space might achieve similar success.

Manual fabrication of the vessels was conducted employing the same resistance welding equipment, coating and/or filler metal, weld schedule and speed for each material and gage which had formerly been used for joining the lap shear specimens. As many successive passes were made as was necessary to consummate a joint completely around the perimeter of the flange. The number ranged from four for most vessels to twelve for the 0.125-inch gage Inconel 718. No particular equipment related problems were encountered during fabrication of any of the vessel assemblies. Presented in the subsequent sections of this report are more detailed descriptions of the fabrication and leak testing of the various materials and gages.

Only the 2014 aluminum specimens were resistance welded. The 0.030 inch and 0.060 inch gage 6Al-4V titanium specimens were joined by resistance brazing employing a 13 weight percent Si-balance Al alloy foil as the filler material. Both the AZ31 magnesium specimens, in all gages, and the 0.090 inch gage 6Al-4V Ti specimens were electroplated with copper which was then coated with the 60 weight percent Sn-40 weight percent Pb alloy, and the surfaces subsequently resistance soldered. The Inconel 718 specimen surfaces were also coated with the 60/40 alloy and resistance soldered to one another or to the similarly coated 6Al-4V titanium specimens.

Leak checking of these vessels was performed in the same manner and on the same equipment as the electron beam welded vessels. A number of non-hermetic seals were discovered in the initial leak tests.

These vessels were discarded and the remainder were subjected to thermal cycling.

The thermal cycling program was conducted in a manner slightly different than was employed for the electron beam welded vessels. It was reasoned that the +250°F end of the cycle could not be obtained reliably by placing soldered specimens into a +400°F oven and any lesser thermal head would make the test program ridiculously time consiuming. Since data was obtained in the feasibility demonstration test phase of the program that indicated no degradation of soldered joints at +250°F, it was felt that the upper temperature limit for the thermal cycling tests could be lowered slightly so long as the total temperature excursion was maintained at 500°F. Therefore, the upper temperature limit was set at +200°F as measured on a thermocouple with the specimens immersed in +300°F oil. The lower temperature was set at -300°F as measured with a thermocouple when the specimens were immersed in liquid nitrogen. One hundred cycles of exposure were imposed. Each cycle consisted of -300°F to +200°F and back down to -300°F.

The specimens were leak checked after thermal cycling and no change in leak rate was noted as may be seen in Table 16.

Spec. Ident.	Material	Cover-Sheet Thickness, in	Joining Process	Helium Leak Rate (cc/sec. @1 atm.)	
				Before Cycling	After Cycling
1AR	2014-T6	0.012	Resistance	$>1 \times 10^{-3}$	Not Tested
2AR	↓	0.012	Welded	↓	↓
3AR	↓	0.012	(no filler alloy)	↓	↓
4AR	↓	0.020	↓	↓	↓
5AR	↓	0.020	↓	↓	↓
6AR	↓	0.020	↓	↓	↓
1MS	AZ-31	0.061	Resistance Soldered	$<2 \times 10^{-10}$	$<2 \times 10^{-10}$
2MS	↓	0.061	(Copper Plated AZ-31	$>2.6 \times 10^{-5}$	$>2.6 \times 10^{-5}$
3MS	↓	0.061	pre-wetted with	$<2 \times 10^{-10}$	$<2 \times 10^{-10}$
4MS	↓	0.071	60Sn-40Pb Solder)	↓	↓
5MS	↓	0.071	↓	↓	↓
6MS	↓	0.071	↓	↓	↓
7MS	↓	0.081	↓	$>1 \times 10^{-3}$	Not Tested
8MS	↓	0.081	↓	↓	↓
9MS	↓	0.081	↓	↓	↓
1TB	6Al-4V-Ti	0.030	Resistance Brazed	$>1 \times 10^{-3}$	Not Tested
2TB	↓	0.030	↓	↓	↓
3TB	↓	0.030	↓	↓	↓
4TB	↓	0.060	↓	↓	↓
5TB	↓	0.060	↓	↓	↓
6TB	↓	0.060	↓	↓	↓
7TS	↓	0.090	Resistance Soldered	$<2 \times 10^{-10}$	$<2 \times 10^{-10}$
8TS	↓	0.090	(copper plated 6Al-4V)	$<2 \times 10^{-10}$	$<2 \times 10^{-10}$
9TS	↓	0.090	↓	$>1 \times 10^{-3}$	Not Tested
1CS	Inconel 718	0.043	Resistance Soldered	$>2 \times 10^{-10}$	$>2 \times 10^{-10}$
2CS	↓	0.043	(unplated Inco 718)	↓	↓
3CS	↓	0.043	↓	↓	↓
4CS	↓	0.078	↓	↓	↓
5CS	↓	0.078	↓	↓	↓
6CS	↓	0.078	↓	↓	↓
7CS	↓	0.125	↓	↓	↓
8CS	↓	0.125	↓	↓	↓
9CS	↓	0.125	↓	↓	↓
1CTS	Inconel 718	0.043 Inco 718 & 0.030 6Al-4V-Ti	Resistance Soldered (unplated Inco 718 copper plated 6Al-4V-Ti)	$<2 \times 10^{-10}$	$<2 \times 10^{-10}$
2CTS	&	↓	↓	↓	↓
3CTS	6Al-4V-Ti	↓	↓	↓	↓
4CTS	↓	0.078 Inco 718 & 0.060 6Al-4V-Ti	↓	↓	↓
5CTS	↓	↓	↓	↓	↓
6CTS	↓	↓	↓	↓	↓
7CTS	↓	0.125 Inco 718 & 0.090 6Al-4V-Ti	↓	$>1 \times 10^{-3}$	Not Tested
8CTS	↓	↓	↓	$<2 \times 10^{-10}$	$<2 \times 10^{-10}$
9CTS	↓	↓	↓	$<2 \times 10^{-10}$	$<2 \times 10^{-10}$

Table 16

DISCUSSION AND SUMMARY

This study has established the feasibility of producing hermetically sound joints with practical structural strength between various gage thicknesses of common structural materials. Neither of the two joining processes appears to be completely satisfactory for all of the applications investigated. However, they tend to complement one another in that the areas in which one process is severely limited, the other seems to work quite well. Both systems can be made operable for the various gages and alloys studied within the maximum allowed electrical power demand of 1800 watts.

Each material combination will be discussed separately in the following paragraphs to provide a summary of the applicability of each of the joining processes.

2014 ALUMINUM

Electron beam welding was an entirely successful joining process for the 0.032 inch gage material, a reasonably successful method of joining the 0.020 inch gage material but is not recommended for applications involving thinner gage stock. The principal problem is that the thermal distortion occurring in the welding of thin gages results in cutting rather than welding unless very rigid tooling can be employed. Such tooling could possibly involve the transport of more mass into space than would be involved if structures were "over-designed" through the use of heavier gage stock. Furthermore, rigid tooling might be so complex that it would tax the astronaut's ability to assemble it in an extraterrestrial environment.

The process, successfully applied, results in hermetically sound joints with helium leak rates less than 2×10^{-10} cc/sec. Thermal shock cycling from $-250^{o}F$ to $+250^{o}F$ for 100 cycles had no effect on the efficacy of the seal. Weld strengths were at the high end of values normally associated with this material in the annealed condition and exhibited little dispersion about their mean values.

Resistance seam welding was successful only in the 0.012 inch and 0.020 inch gages. It was not possible to obtain a sufficiently restricted "hot zone" in the 0.032 inch gage thickness to produce fusion. Resistance brazing of the 0.032 inch gage, using the 13 percent silicon-balance aluminum brazing alloy was also unsuccessful.

Tensile shear strengths of the order of magnitude of 3000 psi were obtained. These values would be quite adequate for structural applications. Unfortunately, all of the leak test vessels tested exhibited helium leak rates of the order of magnitude of 10^{-3} cc/sec.

A possible solution to the problems of obtaining hermeticity and joining heavier gage material by this process would be resistance soldering. The base material could be zinc flashed and copper plated prior to tinning with soft solder. This technique proved successful on other materials involved in this study as will be discussed in subsequent paragraphs. Hermetic seals are readily obtained with low energy and high joining speed. The strength of soldered joints produced by this method, in vacuum, are only slightly lower than resistance seam welded joints. A joint strength of approximately 2000 psi in tensile shear would be a realistic value.

AZ31B MAGNESIUM

Electron beam welding of this alloy, in any gage thickness, is a very marginal application and is not recommended. The process produces severe surface pitting due to vaporization of the alloy which induces arcing in the electron gun. This causes high current surges which produce even more severe arcing. Experience has shown that the process is applicable only to gage thicknesses less than about 0.030 inch if optimum quality weldments are to be obtained. It might be possible to obtain better welds at long gun-to-work distances although this was not investigated.

Electron beam welds of a mechanical strength suitable for structural applications may be obtained but it was not possible to obtain hermeticity in this study. Weld tensile strengths obtained approximated the design allowable values given in MIL-Hdbk 5 for the material in the 0 temper.

Resistance seam welding of this material is possible only in gage thicknesses less than 0.030 inch within the allowed power level. Therefore, the required joints in 0.060 inch, 0.070 inch and 0.080 inch stock were resistance soldered. The material was prepared for soldering by copper plating and hot tinning with soft solder. A rather heavy copper plate, 0.004 inch thick, was used to prevent any diffusion of solder into the magnesium. In retrospect, this was a poor decision because some of the tensile shear test specimens seemed to have failed by peeling of the plate before or, perhaps, as the solder joint failed. If the copper plate thickness were reduced from 0.004 inch to 0.0005 inch, better adhesion would probably be obtained. It should be pointed out that peeling was noted in less than 20 percent of the tensile shear tests. The leak test vessels were produced with only a flash of copper and were tinned and resistance soldered satisfactorily.

In general, this was a highly successful joining method. Joint strengths of approximately 1500-2000 psi in tensile shear were obtained and helium leak rates of less than 2×10^{-10} cc/sec. were achieved. Thermal cycling had no affect on the leakage rate of the joints.

INCONEL 718

Electron beam welding of this material, in the three gages involved, was a highly successful joining method. No problems were encountered in the preparation of the tensile test samples and joint strengths were approximately equivalent to those obtained in the annealed condition.

Helium leak tests revealed the two thinner gages to possess leak rates less than 2×10^{-10} cc/sec. both before and after thermal cycling. Leak rates of the order of magnitude of 10^{-3} to 10^{-4} cc/sec. were obtained with the 0.120 inch gage material. This was probably due to insufficient beam power which caused a lack of completely uniform penetration. There is little doubt that an increase in beam power of, perhaps, 10 or 15 percent would result in sound, hermetic joints.

Initial attempts at resistance seam welding resulted in sound fusion welds only in the 0.043 inch gage thickness. Resistance brazed joints were produced in the 0.043 inch and 0.078 inch gage thicknesses with a gold filler alloy but this practice was not successful for the 0.120 inch gage stock. Consequently, it was decided that the joints should be produced by resistance soldering using a soft solder alloy as a filler.

The base metal was directly hot tinned with 0.005 inch to 0.010 inch of soft solder. Tensile shear strengths of approximately 1500 to 2000 psi were obtained. Helium leak rates were less than 10^{-10} cc/sec. both before and after thermal cycling.

This appears to be a highly successful method of joining this material.

6A1-4V-TITANIUM

Electron beam welding of this material, in the gage thicknesses involved, could be considered to be a highly successful joining technique. No problems were encountered in the preparation of the tensile test specimens and joint strengths approximating those of the material in the annealed condition were obtained.

Helium leak rates of less than 2×10^{-10} cc/sec. were obtained with the two heavier gages both before and after thermal cycling. Leak rates of 10^{-4} to 10^{-7} cc/sec. were obtained with the 0.035 inch gage material. This indicates that too low a beam power was used for welding this series of test vessels. An increase of five to ten percent in beam power would probably be adequate to obtain complete fusion at the joint interface.

Resistance seam welding of this material was found to be successful only in gage thicknesses of 0.030 inch or less. Resistance brazing tests were performed with a number of filler alloys but only the 13 percent silicon-aluminum filler was even moderately successful. Joints were made with this filler alloy in the 0.030 inch and 0.060 inch gage thicknesses but it was not feasible for the 0.090 inch gage thickness. The 0.090 inch gage material was joined by plating the faying surfaces with 0.001 inch of copper, hot tinning the plated surface with soft solder and resistance soldering the joint. An 0.007 inch thick soft solder coating worked well.

Tensile shear strengths of the resistance brazed joints averaged approximately 10,000 psi while the resistance soldered joints had tensile shear strengths of approximately 3000 psi.

Helium leak tests showed all of the resistance brazed vessels leaked at rates in excess of 10^{-3} cc/sec. Two of the three soft soldered vessels had leakage rates less than 10^{-10} cc/sec.

Resistance brazing does not appear to be an acceptable method of producing hermetic joints although they possess suitable structural strength. Resistance soldering appears to be a potentially feasible method of joining titanium.

6Al-4V-TITANIUM TO INCONEL 718

Electron beam welding of this combination is completely impractical in any gage thickness because of the inherent brittleness of the joint. It is not recommended under any circumstances.

Since such poor results were obtained in electron beam welding this material combination, it was assumed that equally poor results would be obtained by virtually any fusion welding process. Therefore, no attempt was made to resistance seam weld this combination. However, joints were produced by resistance soldering that were quite successful. The alloys were tinned with soft solder by the procedures described earlier. Tensile shear strengths of approximately 4000 psi were obtained. Helium leak rates of less than 2×10^{-10} cc/sec. were obtained in all but one vessel both before and after thermal cycling.

Resistance soldering appears to be a highly practical method of joining these two materials.

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2. "The Effect of Pressure on the Gas Metal-Arc Welding of Aluminum Alloys," G.R. Salter, British Welding Research Association, Welding Research Supplement, March 1965, pp. 107s ff.

   Work was more oriented to hyper baric pressure but some data to indicate better energy coupling in vacuum but poorer penetration limiting usage to thin sections.

3. "Improved Weld Strength in 2000 Series Aluminum Alloys," D.E. Schillinger, et al, Frankford Arsenal, Welding Research Supplement, June 1963, pp. 269s ff.

   Describes effect of steep thermal gradients induced by sub-ambient chilling systems upon mechanical properties.

4. "Improved Strengths in Welded High-Strength Heat-Treatable Aluminum Alloys," F.R. Collins, Alcoa, Welding Research Supplement, August 1962, pps 337s ff.

   General article on fusion welding of 2014, 2219, 7075 and 7178 alloys.

5. "Automatic Gas Tungsten-Arc Welding of Magnesium," L.F. Lockwood, Dow, Welding Research Supplement, May 1965, pps 214s ff.

   Significant data on weld current characteristics versus scarifying action of arc and resultant weld soundless and strength.

6. "Seam Welding of MA8 Alloy with Hermetically Sealed Seams," A.A. Chakalav, et al, obtained from AFSC Foreign Technology Division, AD 609157.

   Discussion of power requirements, typical defects and corrective practices for roll-seam welding magnesium.

7. "Welding Nickel Base Alloys," R. D. Beemer and L. J. Mattek, GD/Convair, Welding Research Supplement, June 1962, pps 267s ff.

Information on TIG and resistance spot welding of thin gage Rene 41 and Hastelloy X.

8. "The Welding and Brazing of Alloy 718," DMIC Report No. 204

9. "Joining of Nickel Base Alloys," DMIC Report No. 181.

10. "Gas Tungsten-Arc Welding Heavy Aluminum Plate," J. A. Liptak, Kaiser Aluminum, Welding Research Supplement, June 1965, pps 276s ff.

Inappropriate to our problem although interesting.

11. "Pigma Welding – A Method for Reducing Weld Porosity," R. B. Barker, Dow, Welding Research Supplement, January 1965, pps 1s ff.

Welding at hyperbaric pressure to minimize porosity. Inappropriate.

12. "Porosity in Titanium Welding," D. R. Mitchell, Timet, Welding Research Supplement, April 1965, pps 157s ff.

Extremely interesting paper but not highly applicable to this program.

13. "Welding High Strength Aluminum Alloys," I. B. Robinson, et al, Alcoa, Welding Research Supplement, May 1962, pps 221s ff.

14. "The Cryogenic and Elevated Temperature Properties of 'Super Alpha' Titanium Alloy Weldments," D. R. Mitchell and D. L. Day, Timet, Welding Research Supplement, March 1963, pps 134s ff.

15. "Properties of Welded High-Strength Titanium Alloy Sheet," A. J. Brothers, et al, JPL, ASTM Transactions, Vol. 63, pps 646 ff.

16. "Gas Metal-Arc Welding of AZ31B Magnesium Alloy Sheet," L. F. Lockwood, Dow, Welding Journal, October 1963, pps 807 ff.

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18. "Review of Recent Developments in Metals Joining," DMIC, 11 June 1965.

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21. "Selected Welding Techniques II," NASA/Marshall, NASA Report No. SP-5009.

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23. "The Promotion of Wetting and Brazing," S. Weiss, MIT, Industrial Liaison Program, Preprint No. 547.

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25. "Final Report on Research and Development of Titanium Rocket Motor Case Vol. III. Development of Welding Practice," Pratt and Whitney Division, United Aircraft Corporation, Technical Report No. WAL 766.2/1-14.

26. "Physical and Mechanical Properties of Pressure Vessel Materials for Application in a Cryogenic Environment, Part II," GD/Convair, Technical Report No. ASD-TDR-62-258 Part II.

27. Minutes of Aluminum Welding Symposium, NASA/Marshall, July 7-9, 1964.

28. "Diffusion in Titanium and Titanium Alloys," R.P. Elliot, Armour Research Foundation, AD 290336.

29. "A Limited Evaluation of Ultrasonic Spot Welds in X2020-T6 Aluminum Alloy Sheet," W.E. Ulery, McDonnell Aircraft, AD 431624.

30. "Development of Ultrasonic Welding with Emphasis on Producing Hermetic Seals," J.B. Jones, Aeroprojects, Inc., AD 600597.

31. "Investigation of Ultrasonic Welding of Refractory Metals and Alloys," Aeroprojects, Inc., AD 296275.

32. "Material-Titanium – Commercially Pure, Ti-6Al-4V, Ti-5Al-2/2Sn. Static and Fatigue Strength of Dissimilar Alloy Spot Welds," E.K. Winslow, et al, GD/Convair, AD 407621.

33. "Seam Welds with Ti-6Al-4V Titanium Sheet," H.H. Stier, GD/Convair, AD 407588.

34. "Observations of Delayed Cracking in Welded Structures of Unalloyed Titanium Sheet," R.H. Ernst, et al, DMIC, AD 602478.

35. "Fusion Welding of Aluminum: An Annotated Bibliography," H.B. McCormick and P.R. Stromer, Lockheed MSD, AD 431626.

36. "Mechanical Properties of 6Al-4V-Titanium Weldment," J. Krieg, McDonnell Aircraft, AD 431633.

37. "Diffusion Welding," M.J. Alborn, Marquardt, Machine Design, September 1965.

Reports successful bonding of Al, 6061 Mg (HK31), Inco 718, Ti-6Al-4V as well as dissimilar metal welding. Required is heat, time and pressure. Some Ti welds have been made in 10 minutes at 50 psi and 1700° F. Joint efficiencies of 85/100 percent obtained.

38. "Solid State Bonding," M.J. Alborn, Marquardt, Welding Journal, June 1964, P 491-504.

This is mostly a background article describing equipment, atmospheres, materials. Very little specific information or data.

39. "Solid State Bonding of Aluminum to Nickel," S. Storckheim, J.L. Zambrow and H.H. Hausna. Trans. AIME, February 1954, pp 269-274.

Pure Ni and 1100 Al were pressed together in vacuum at various temperatures and pressures for various times. Excellent bonds were achieved, i.e., 20 KSI by using 500° C and 40KSI for 4 minutes; 6KSI by 500° F and 22KSI for 4 minutes.

40. "Low Temperature Diffusion Bonding of Aluminum Alloys," I. M. Barta, NAA, Columbus, Welding Research Supplement, June 1964, pp 241-247.

2219-T81 and 6061-T6 exhibited best self bonding ability. Maximum shear was 5.6 KSI from 870° F — 4 hours. Use of Alclad as a diffusion aid gave 9-11 KSI from 325° F and 24 KSI for 1 hour. Plasma spraying was also an excellent aid. Vacuum or inert gas was not required.

41. "Metallographic Studies of Al-Ni-U Bonds in Nuclear Fuel Elements," C. L. Angerman, DuPont, Trans. ASM, Vol. 54, 1961, pp 260-275.

42. "Explosive Welding of Aluminum Alloys," H. Addison, W. E. Fogg, I. G. Betz, F. W. Hussey, Frankford Arsenal, Welding Research Supplement, August 1963, pps 359-364.

1/16 inch 2024-T3 Al sheet-lap welds with 1/2 inch overlap were made in air using primacord.

43. "Brazing René 41 Honeycomb Sandwich Structures," A. O. Vanaman, J. W. Greagor, Republic Aviation, Welding Research Supplement, August 1963, pp 353-358.

Various brazing alloys — some in plastic sheet, some metal foil, some powder were used successfully at 1800° - 2150° F for 15 minutes in argon or vacuum. The Ni-Cr-P alloy allowed use of 1800° F (approximately sol. temperature of Inco 718).

44. "Brazing of Thin Gage René 41 Honeycomb," L. H. Stone, A. H. Freedman, E. B. Nukus, Northrup, Welding Research Supplement, September 1963, pp 397-403.

Ni base plus Cr-Si-Mn braze alloys were evaluated using quartz lamp heat source. The brazing was done in argon, at 2120° F — 3 minutes after controlled heating rate. Schedule was — to 800° F at 700° F/min — hold 8 minutes, raise to 1000° F — hold 5 minutes. The braze material was in powder form held together by a bindle burned off during heating.

45. "A New Brazing Alloy for Age-Hardenable Super Alloys," J. F. Berker, P. R. Mobley, T. K. Redder, General Electric, Welding Research Supplement, September 1962, pp 409-412.

46. "Soldering of Titanium Alloy AT-3 with Application of Various Galvanic Coverings," A. Y. Shinyayev, V. V. Bondarev, USSR Inst. Metall., November 1963.

47. "Study of Low Melt Brazing Alloys," J. Glasser, W.E. Few, Chem. and Metall. Research, Inc , February 1965. AFML Project 8-250.

48. "Recent Progress in Development of Self-Fluxing Air Proof Brazing Alloys," N. Bredys, H. Schwartbart, ARF, Welding Research Supplement, March 1961, pp 123-129.

Review of Cu with low Li/B ratios.

49. "Explosive Welding," R. J. Carlson, Battelle MEG, August 1965, pp 57-60.

50. "High Strength Titanium Bonding by Torch Heating," K.M. Weigert, Penn State, Welding Research Supplement, February 1962, pp 84-88.

51. "Brazing Investigation of Several Candidate Materials for Thrust Chamber and Heat Exchanger Applications," H.S. Rabensteine, Marquardt AF Contract 33(657)-8706, June 1963.

Includes results of Brazing René 41, 6061, Ti-5Al-24SN.

52. "Evaluation of Brazing Alloys for the Fabrication of Inconel 718 Honeycomb Sandwich Panels," F. J. Coffey, McDonnel Aircraft, July 1963.

Four Au-containing braze alloys were evaluated.

53. "Engineering Research – Brazing Alloy – 'Dynabraze B' Composition Optimization of," W.M. Pratt, General Dynamics, December 1962.

This is a 95 percent Ag - 5 percent Al + Mn brazing alloy for Ti (RS 140 Ti was used).

54. "Application of Explosive Bonding," J. J. Douglass, DuPont ASTME, 1965.

A wide variety of metals may be joined by this process. Unfortunately this paper is mostly an advertisement for DuPont and presents almost no technical information of any use.

55. "The Brazing of Ti to Al," F. Bollenrath, G. Metzger, Welding Research Supplement, October 1963, pp 442-452.

Satisfactory joints were achieved by dip brazing in motion flux with a Ag-33 percent Al and with Al-50 percent Zn. Somewhat less satisfactory joints were made by torch heating. Difficulty of joining these two materials is due to the widely different values thermal diffusivity values. This makes it difficult to bring both members to the same temperature.

56. Energy Properties of the Electric Welding Arc, G.M. Tikhodeyev, FTD-TT-62-18181/1+2, 6 August 1963, Translation Division, Foreign Technology Division, USAF.

A highly theoretical 302 page treatise on the physics of the electric arc. May not be directly useful to program but is being studied as a background reference on arcs in gaseous environments.

57. Structure and Properties of Titanium Alloy Weld Joints, V.M. Grabin, et al, USSR, Department of Commerce Clearinghouse, Accession No. N65-19591.

Not too useful. Concerned generally with mechanical properties of titanium weldments. Fairly well parallels American technology.

58. "Effect of Plastic Deformation on the Structure and Properties of VT14, VT15 and VT16 Weld Joints," S.G. Glazunov, USSR, Department of Commerce Clearinghouse, Accession No. N65-20293.

Discusses the improvement of mechanical properties of titanium weldments by post weld planishing and heat treatment.

59. The Arc Welding of Aluminum, AD 115760.

Rather old material but useful as reference.

60. "The Effects of Gaseous Contaminants in the Welding Atmosphere on the Surface Color and Hardness of Weld Deposits on Ti-721 Alloy Titanium Plate," R. J. Wolfe and A. L. Chick, USN Applied Science Laboratory, AD 456249.

Scientific confirmation of old information, not useful to this program.

61. Welding 2014-T6 and 2024-T86 Aluminum Alloy Sheet, D.E. Schillinger, Frankford Arsenal.

Discussion of minimal energy input as a requirement for good welds in 2XXX alloys.

62. "Investigation of Modified Position, Down-Hand MIG Welding of 2014-T6 Aluminum Alloy," J. Haryung, Douglas Aircraft Co., Report No. SM-48366, 4 December 1964.

Discussion of weldability of 2014-T6 aluminum, otherwise, of no applicability to program.

63. "MIG Welding Titanium Using a Non-Reactive Flux," R.A. Rosenberg, Mitron Corp., AD-441259.

64. "TIG Welding Titanium Using a Non-Reactive Flux," R.A. Rosenberg, et al, Mitron Corp.

Both of these references describe the use of a proprietary "root flux" for titanium which allows use of a sort of "Unionmelt" process on titanium.

65. "Characteristics of D-C Arcs with Titanium Anodes and Tungsten Cathodes in Inert Gas Systems," T.B. Jones and E.H. Young, Watertown Arsenal.

Old work but contains useful information.

66. "Porosity and Solidification Phenomena in Aluminum Welds," Z.D. Saperstein and D.D. Pollock, Douglas Aircraft Co., AD-N65-21450.

An interesting paper but not particularly useful to this study.

67. "Development of Welding Techniques and Filler Metals for High Strength Aluminum Alloys," N.G. Lemmond, J.M. Donald, K.K. Sperry, Southwest Research Institute, AD-N64-29705.

Development of welding techniques for 2219 aluminum in heavy sections.

68. "Second All-Union Conference on Welding Dissimilar Metals," USSR, AD-N65-26211.

Summary of recent Russian welding research. Their stated problems and programs generally parallel Western work. Nothing in reference that would be useful to this program.

69. "New Developments in the Welding of Metals," R.J. Rieppel, DMIC, AD 240764.

A useful, but old, review of welding technology.

70. "Studies of High-Frequency Welding Process," W.R. Byrne, J.J. Vagi and D.C. Martin, Battelle, AD-N-64-29566.

High frequency resistance welding offers excellent joint strength efficiency. It is especially well suited for making square butt joints for closing rolled tubes (as rocket motor cases). Unfortunately, force and power requirements are too high for use in space and joint tooling would present some difficult problems.

71. Explosive Welding, Vasel Philipchuk, American Potash and Chemical Corporation, August 1961, AD 268015.

Ti-6Al-4V sheet was welded to itself. The welding required a base and the explosion was in water. The author gave no data but stated that the explosive must be carefully controlled since too little or too much does not perform satisfactorily. Too much results in burning.

72. "Colloquium on Brazing of Metals at the XVI Congress in Helsinke 1963," Ya.K. Alekseyea, N64-38514, Welding Production, No. 6, 1963.

This article reports on papers presented and is very general in nature.

73. "Bonding and Welding of Dissimilar Metals," L.F. Gatsek, S&ID NAA, N65-18528.

This is a review of various joining methods for dissimilar metals. It includes EB ultrasonic, TIG and resistance welding as well as soldering and brazing. Some of the combinations of interest are Al to Ti, Al to Ni, Ti to stainless steel, Al to stainless steel.

74. "Brazing Titanium Using an Electroplated Copper Coating," V.V. Bondarev, Z.V. Nekeforovs, I.V. Bankorskaya, Welding Production, No. 9, 1964, N65-11678.

Electrodeposited Cu was used on Ti (10-30 microns). A 68 percent Ag – 27 percent Cu – 5 percent Sn braze alloy was used in the form of 0.5 mm foil. Pressure of 3-5 KSI was used in a vacuum (10^{-3} mm Hg) and a temperature of 780-840°C. Strengths of 25-50 KSI were obtained but control of temperature was critical since braze joint strength decreased with increasing temperature.

75. "Explosive Welding," H. J. Addison, Jr., Frankford Arsenal, ASME 1964, N65 10656.

Explosive welding can be used for dissimilar metals, spot and seam welding and cladding. Lap, tee, and edge joints have been made. The strength of the weld is essentially that of the base material. Members to be welded must be placed between explosive and an anvil necessary to absorb energy.

76. "Diffusive Brazing of Nonferrous Metals and Its Possibilities," N. F. Lashka, S. V. Lashka, Nonferrous Metals, No. 8, 1964, N65 11318

This is a fundamental paper on high temperature brazing. Diffusion brazing can produce joints with higher useful temperature than the brazing temperature. This is possible by the formation of higher melting point intermetallics and by the solution of a higher melting point component thereby producing a higher melting point alloy.

77. "Investigation of Diffusion Processes in the Brazing of Titanium Alloys," A. Ya. Shinyayev, V. V. Bondarev, Metallurgy, Metal Science and Physico-Chemical Investigation Methods, No. 12, 1963, N65 20004.

This work is similar to Reference 74 except that a nickel-cobalt electrodeposited film was used. In both projects, the surface of Ti was hydrided by hot H_2SO_4 pickling. The use of a vacuum removed the hydrogen during brazing.

78. "Brazing Titanium with Copper-Base Alloys," B. N. Pereveyentsev, V. V. Koylov, Welding Production, No. 9, 1964, N65 11678.

Tensile strengths of 25-40 KSI were achieved in braze joints brazed at 825° C for 5 minutes. Heating rate must not be less than 25° C/minute.

79. "Structure Features and Diffusion Mobility in Titanium Alloys in Different Phase States," S. Z. Bokshteyn, T. A. Yemelyanova, S. T. Kishkin, and L. M. Mersky, Diffusion Processes, Structures and Properties of Metals, 1964, N65 20291.

This is a fundamental study of diffusion rates of various elements in Ti. It established that Sn diffuses much faster in alpha Ti than beta Ti and diffusion permeability of equiaxed alpha gains is less than that in acicular alpha phase.

80. "Brazing of Titanium with Rapid Heating," I. I. Slyevskiy and N.S. Kochukov, Welding Production, No. 5, 1963, N63 22966

Salt bath ($BaCl_2$) heating was attempted but caused rapid oxidation of the Ti. The work also showed that using Ag as a band for Ti is extremely difficult due to an intermettalic brittle compound. The time at temperature must be carefully limited.

81. Development of Low Temperature Brazing Alloys for Titanium Honeycomb Sandwich Materials, W.C. Troy, Solar Aircraft, January 1963, N63 15878

This study was concerned with obtaining braze joints at temperatures below 1100° F. Ag-Cu-Ge alloys were satisfactory below 1100° F and were used in argon and under vacuum. Lap shear strengths of 6-10 KSI were obtained.

82. Joining Aluminum to Stainless Steel, M. C. Smith and D. D. Rabb, NBS-AGC, Boulder, Colorado, March 1955, AD-121542.

Aluminum is best soldered by first tinning, or zincating then Cu plating or nickel plating. This work was with 300 series stainless steel, however coated Ti or Ni base alloy would work in the same manner.

83. Brazed Titanium Lap Joints, Mechanical Properties, Oxy-Acetylene Torch Heated, L. D. Girton, Convair, 1955, AD-125800.

Shear strengths of 27 KSI were achieved in 1/8" unalloyed titanium lap shear joints using fine silver heated by oxy-acetylene torch. The flux used was a mixture of Ag, K and Na chlorides plus LiF.

84. Brazing Titanium Sandwich Construction, J. F. Rudy, R.M. Necheles, H. Schwartbart, ARF, 1959, AD-207904.

This is a study of various brazing alloys used to join various Ti alloys to stainless steel. Quartz lamps in protective atmosphere were used as a heat source. Temperatures used were 1500-1600° F for 15 minutes or less. A Ag-28 Cu-0.2 Li and a Ag-0.25 Mg-0.2 Ni-1 Li brazing alloy was found to be satisfactory.

85. Gas-Flame Brazing of Metals, G. A. Asinovskaya, Moscow, 1963, N64 18977.

This is a comprehensive text on the state of the art of gas-flame brazing in the USSR.

86. Explosive Forming and Welding of Honeycomb Sandwich Material, Martin Company, Denver, October 1964, N64 33922.

This report contains some work of interest concerning TIG welding of 6061 Al to 2014 Al. Various thickness plates were welded. The explosive portion of the investigation was directed solely to the forming of the welded sandwich structure.

87. "Certain Problems Involved in the Brazing of Titanium Alloys," A. Ya. Shinyayev, V. V. Bondarev, and A. A. Baykov, Welding Production, No. 10, 1963, N64 11271.

This is a study of the use of various electro-deposited coatings to serve as a diffusion braze for Ti in the temperature range of 1350°-1650° F for 15-25 minutes. Joint strengths of 10-50 KSI were obtained.

88. "Brazing with High-Temperature Solders," V. A. Gorokhov and M. I. Skripov, Herald of Machine Building, No. 7, 1955, N64 10354.

Successful braze joints were made in the 900-1250° C range using three different high temperature solders, copper base, nickel base and chromium base. Welding torch was used as a heat source.

89. "Evaluation of Brazed Honeycomb Sandwich with 6061 Face Sheets and 3003 Core," J. Krieg, McDonnell Aircraft, August 1963.

This is a short report showing micros and micro-hardness of a joint. The significance is that the joint was made without a flux using an unnamed braze material made by Tri-Metal Works of Riverton, N. J.

90. S. Podlaseck and J. Suhorsky, "Stability of Organic Materials in a Vacuum", Martin Marietta Corporation, Space Systems Division, Report RM-150, April 1963.

It has been suggested that exposure of adhesives to low pressure may produce volatilization of materials and a subsequent weakening of the bond. Furthermore, if the porosity of the glue line is increased, permeability will increase if a pressure differential exists across the bond.

In order to determine the extent of this problem, long term exposures up to 1100 hours at 93 to 121°C in vacuum have been conducted. In these tests, using nine commercial adhesives, bonded specimens were periodically checked for leakage. With the exception of one modified phenolic-supported adhesive film, results indicated that the adhesives were stable in the test environment.

On the basis of the limited testing conducted to date, it does not appear that a high vacuum will cause significant deterioration for most of these materials.

91. Claus G. Goetzel, John B. Rittenhouse, John B. Singletory, Editors, "Space Materials Handbook", Second Edition, Lockheed Missiles and Space Company, January 1965.

Chapter 13 deals with adhesives and considers, in turn, the effects of various space environments. Polymeric adhesives are classified into three groups depending upon their use: Structural, non-structural, and optical. The structural adhesives are chemically typified by such polymers as epoxides, polyurethanes, phenolics, certain silicones, and copolymers of vinyl, nylon and acrylonitrile with phenolic or epoxide resins. The non-structural adhesives are (1) air-dry solvent systems of natural or synthetic rubbers, (2) low molecular weight thermoplastic resins, and (3) filled and unfilled room temperature, contact pressure curing thermosetting resins. Optical adhesives are special non-structural materials, which because of their optical properties are used in cementing lens components etc. The adhesive properties discussed are tensile-shear strength, peel strength, fatigue, creep, optical transmission and thermal qualities.

Effects of high and low temperatures — Up to 500°F most adhesives undergo gradual softening and strength reductions. Above 650°F depolymerization, pyrolysis or rapid degradation will begin. At low temperatures, all the structural adhesives reported increased strength or retained good shear strength values down to -100°F. At much lower temperatures, e.g., -320°F and below, bond strengths gradually decrease but may still be above room temperature values. Bonds at these temperatures are generally quite brittle, have reduced impact strength and resistance to vibration and tensile-compression fatigue life.

Effects of nuclear radiation — Energy from electrons, protons, neutrons and gamma rays may be absorbed by the adhesive bonds and cause cross-linking or chain scission of the polymers. The damage threshold for a change to occur in a significant mechanical property is below 10^9 rads at room temperature. In general, adhesives developed for high temperature use, such as the phenolic epoxy types, resist radiation better than thermoplastic and general purpose types. Adhesives such as Shell 422-J have excellent radiation stability at room temperature, retaining useful strength properties to an exposure of 10^9 rad. Others tested show equally good resistance but do not have as high a temperature resistance. Fillers such as glass fibers, mica and asbestos generally improve radiation stability. Aromatic curing agents generally produce more radiation-resistant compositions than do the aliphatic curing agents. The radiation levels at which these adhesives retain their structural properties suggest a useful life in an outer space average environment of approximately five years.

Effects of high vacuum — Since bonded joints present very little adhesive surface area to the vacuum environment of space and because adherend materials are relatively impermeable to gases, the effects of vacuum on mechanical properties of adhesives are insignificant for most applications. Hence, outgassing of volatile products of the adhesive can occur only through the glue line edges which are usually less than 0.010 inch thick. Diffusion through the polymer matrix to the edges is, therefore, the controlling mechanism. Studies have indicated that this is an extremely slow process. High vacuum can, however, induce porosity in the glue line. This effect is compounded by the absorption of high energy radiation that increases the yield of volatiles. Studies have shown, however, that with the selection of optimum adhesives, the porosity problem is minor.

Effects of ultraviolet radiation on adhesives — This environment is of no consequence to adhesive bonded structures and parts having opaque adherends since all metals and structural plastics absorb ultraviolet radiation completely within about the first 100-μ thickness of material from the exposed surface. The adhesive is thus protected except possibly for the exposed glue-line edges. For applications where direct exposure to sunlight occurs and where optically transparent adherends are used, ultraviolet radiation effects on the adhesive constitute an important design consideration. Such adhesives may undergo photochemical decomposition manifested by changes in spectral or optical properties such as darkening and increased solar absorptivity which results in reduced light transmission and increased glue-line temperatures. The mechanical properties such as tensile-shear and peel strengths may be reduced in a manner similar to but somewhat less drastic than in the case of nuclear radiation. These effects may be minimized by utilizing adhesives having optimum ultraviolet stability and adherends which are inherently opaque.

92. F. J. Clauss, "Materials in the Space Environment", presented at Sixth Annual Symposium on Space Environmental Simulation, 17-18 May 1965.

The series of adhesives listed in the following table were subjected to vacuum and temperature and to gamma radiation from a cobalt-60 source. Specimens were in the form of magnesium cylinders which were capped at each end with magnesium discs bonded in place with the adhesive under study. The interior of each tube was evacuated through a side tube.

Chemical Type	Form	Cure Cycle
Epoxy - Phenolic A	Supported film	25 psi, 30 min. 240°F; then 25 psi, 30 min. 330°F.
Epoxy - Phenolic B	Supported film	5 psi, 60 min. 330°F; then 75 psi, 60 min. 330°F.
Vinyl - Phenolic	Supported film	5 psi, 8 min. 300°F; then 250 psi, 30 min. 310°F.
Epoxy - Polyamide	Two-part liquid	5 psi, 24 hr. 77°F; then 60 min. 165°F.
Epoxy A	One-part liquid	50 psi, 60 min. 350°F.
Epoxy B	Two-part liquid	5 psi, 60 min. 220°F.
Epoxy C	Two-part liquid	5 psi, 90 min. 220°F.
Epoxy D	Two-part liquid	5 psi, 24 hr. 77°F; then 60 min. 165°F; then 60 min. 220°F.
Silicone	One-part liquid	24 hr. 77°F.

Periodically, the specimens were tested for leakage. The exposures were for over 1100 hours at a pressure of the order of 10^{-6} mm. Hg. and temperatures of 200-250°F. Results indicated that the adhesives were quite stable in this environment with the exception of a modified phenolic supported film adhesive, which leaked badly.

After this exposure, the specimens were removed from the vacuum system and irradiated for a total dosage of approximately 3×10^7 rad. each. They were then exposed to the temperature vacuum condition as before. Finally, mechanical tests were performed on the specimens and the adhesive properties compared with unaged "control" specimens. High vacuum did not affect either the strength or porosity of structural adhesive bonds. Even when subjected to simultaneous exposure to elevated temperatures of 250°F, adhesive leak rates were generally well below 10^{-5} cm^3/sec. Nuclear radiation, on the other hand, produced somewhat greater effects on glue-line porosity.

93. H. H. Levine, "Recent Developments in High Temperature Adhesives", paper presented at the Adhesives Symposium, Picatinny Arsenal, Dover, New Jersey, September 27-28, 1961.

Because oxidation is an important factor in degradation of adhesives at high temperature, a study was made of performance in nitrogen. The data show that in a nitrogen environment serious degradation did not begin even after an exposure to 600°F for almost 190 hours. It is indicated that such thermal stability would be present also in a high vacuum environment.

94. E. A. Dewitt, S. Podlaseck, and J. Suhorsky, "Effects of Low Pressure at Elevated Temperatures on Space Vehicle Materials", The Martin Company, Baltimore, Maryland, M-RM-29, Research Memorandum, March 1959.

They reported on two adhesives exposed to vacuum and elevated temperature. The adhesive FM-47, after exposure for 3 1/2 hours at 250°F in a vacuum of 4.2×10^{-4} mm Hg. decreased in peel strength by 13 percent and 7.1 percent in shear strength. The second adhesive, HT-424, was exposed to 450°F for 4 hours in a vacuum having an ultimate pressure of 5.9×10^{-4} mm Hg. and showed a 14 percent decrease in peel strength and 0.6 percent in shear strength.

95. P. E. Gray, G. K. Cornelius, J. D. O'Donnell, and W. W. Howard, "Rockets in Space Environment, Volume I, The Experimental Program", Aerojet-General Corporation, Azusa, California, RTD-TDR-63-1050, Final Report, AF 04(611)-744, February, 1963.

The authors irradiated in vacuum at ambient temperature specimens prepared with epoxy, epoxy-phenolic, vinyl-phenolic, nitrile-phenolic and glass supported epoxy film adhesives. They were tested at -300°F for ultimate shear strength. The tests indicated that the space environment had no effect on lap shear strength. It was noted that specimens prepared with epoxy-phenolic, glass supported epoxy film, and vinyl-phenolic appeared to be only slightly affected by vacuum. The effect was

small enough so that the original strength of the adhesive can be considered adequate as a design value. Epoxy and nitrile-phenolic adhesive bonded specimens showed no indication of deterioration.

96. L. Isenberg, "Plastic Materials in Aerospace Environment", ASTIA Report No. AD 435245, November, 1963.

This is a general survey of the space environment and its effect on non-metallic materials. It presents data on radiation effects for lap shear specimens bonded with 422-J epoxy phenolic, AF-32 nitrile phenolic and FM-1000 nylon-epoxy adhesives. Of special interest, however, are stress-strain curves for these tests. Actual changes in modulus of elasticity are given. These changes were insignificant except for the AF-32 which showed an increase in modulus and a slight decrease in ultimate tensile shear strength.

97. H. M. Abbott, "Space Environmental Effects on Seals, Gaskets, Adhesives, and other Elastomeric and Polymeric Materials", an annotated bibliography, Lockheed Aircraft Corporation, Sunnyvale, California, under Contract AF 14(647)-673, September 1961.

This is a 218-page bibliography with 558 annotated references including a materials index. These references were compiled as an aid to future research efforts concerning the problems of evaluating space environmental effects on various materials to perform specific functions and to indicate what materials appear most suitable for use in spacecraft. Environmental conditions covered are exposure to high vacuum, service temperatures, and radiation (both ultraviolet and high-energy). Materials used for inflatable space vehicles and structures are included as general applications of plastics or polymers.

98. R. D. Hibben, "USAF Studying Space Tool Development", Aviation Week and Space Technology, September 13, 1965.

This magazine article reports the needs of the Air Force in certain areas of technology. It tells of the ideas currently being explored and the programs being pursued. Conditions to be encountered are -150°F to +250°F in a 10^{-12} torr vacuum. Joining techniques must be capable of bonding different kinds of materials used in fabricating spacecraft, while at the same time being safe for astronauts to use both inside and outside the craft. Temperature requirements for adhesive bonding go up to about 600°F. Applications - anchoring astronauts and equipment to work sites. The Air Force wants systems with curing times of 10-15 seconds and which can be operated by low-powered D-cell nickel cadmium batteries. Tensile and shear strength requirements are at least 100 psi.

99. E. E. Kerlin, "Investigation of Combined Effects of Radiation and Vacuum and of Radiation and Vacuum and of Radiation and Cryotemperatures on Engineering Materials, Volume 1, Radiation-Vacuum Tests", General Dynamics/Fort Worth FZK-161-1, Annual Report, November 9, 1961 - November 8, 1962, NAS 8-2450, January 5, 1963.

100. F. J. Clauss, "Materials and Components in Space Environments", Paper presented at the Institute of the Aerospace Sciences 31st Annual Meeting, New York, N. Y., IAS Paper No. 63-58, January 1963.

101. Blackmon, P. H., F. J. Clauss, G. E. Ledger, and R. E. Mauri, "Materials Evaluation Under High Vacuum and Other Satellite Environmental Conditions", Lockheed Aircraft Company, Sunnyvale, California, Technical Report No. 3-77-61-23, AF 04(647)-787, January 1962.

102. G. Yasui, "RIFT Radiation Effects Program Irradiation No. 1 and 2 - Cryogenic Insulation Materials", Lockheed Aircraft Corporation, Missiles and Space Company, Sunnyvale, California, NSP-63-35, NAS 8-5600, May 7, 1963.

103. G. Yasui, "Thermal Insulation Material Tests (Cryogenic)", Lockheed Aircraft Corporation, Lockheed-Georgia Company, Marietta, Georgia, ER-6512, pp 37-69, September 10, 1963.

104. N. J. Broadway, R. W. King, and S. Palinchak, "Space Environmental Effects on Materials and Components", Battelle Memorial Institute, Columbus, Ohio, Report RSIC-150, 1 April, 1964.

105. F. J. Clauss, "Evaluation of Materials for Spacecraft Applications", Lockheed Missiles and Space Division, Sunnyvale, California, Report 5-10-61-11, June 1961.

106. J. A. Black, D. J. Lyman, D. B. Parkinson, "Development of Material Specifications and Qualifications of Polymeric Materials for the JPL Spacecraft Materials Guidebook, 1. Epoxide Adhesives", Stanford Research Institute, Menlo Park, California, SRI Project PRD-5046, June 15, 1965.

107. L. D. Jaffe, J. B. Rittenhouse, "Behavior of Materials in Space Environments", Jet Propulsion Laboratory, Pasadena, California, Technical Report No. 32-150, November 1, 1961.

108. J. P. Thomas, R. J. Stout, "Effects of Elevated Temperature and Reduced Atmospheric Pressure on Adhesives, Potting Compounds and Sealants", General Dynamics, Fort Worth, Report ERR-FW-129, 30 December 1961.

109. H. S. Schwartz, R. W. Farmer, "Thermal Irradiation of Plastic Materials", Aeronautical Systems Division, Wright-Patterson AFB, Ohio, WADD TR 60-647, August 1961.

110. F. W. Kuhn, G. P. Peterson, R. C. Tomashot, "Plastics, Adhesives, and Composite Materials", In: Proceedings - Materials Symposium, sponsored by the USAF Aeronautical Systems Command, Phoenix, Arizona, 13-15 September 1961.

111. D. M. Newell, "Radiation Damage to Plastics", In: SPE Journal 14 (7):17 (July 1958), Convair, Division of General Dynamics Corporation, Fort Worth.

112. Detailed Techniques for Preparing and Using Hard Gallium Alloys, George G. Harmon, National Bureau of Standards, Technical Note 140, April 1962.

This report presents an expansion and clarification of techniques for preparing and using dental-amalgam type gallium alloys for industrial and scientific uses that were previously published in the Review of Scientific Instruments.